NPDGamma Liquid Hydrogen Target Engineering Document

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Introduction (M. Snow, 6-20-01)

This document consists of a general description of the design, operation, and safety aspects of the liquid parahydrogen target for the NPDGamma experiment. The purpose of this experiment is to search for parity violation in the angular distribution of 2.2 MeV gammas produced by polarized cold neutron capture in hydrogen. The experiment therefore requires a hydrogen target. For the purposes of this document we will define the "target" broadly to include (1) the target cryostat and vacuum system inside the experimental cave, where the neutron captures take place, (2) the gas handling and target control system external to the cave, and (3) the safety system, including the relief valves and blowoff stack. A conceptual diagram of the overall experiment is shown in Figure 1. A conceptual sketch of these components of the overall system is shown in Figure 2. Figure 3 shows the legend for the gas handling system.

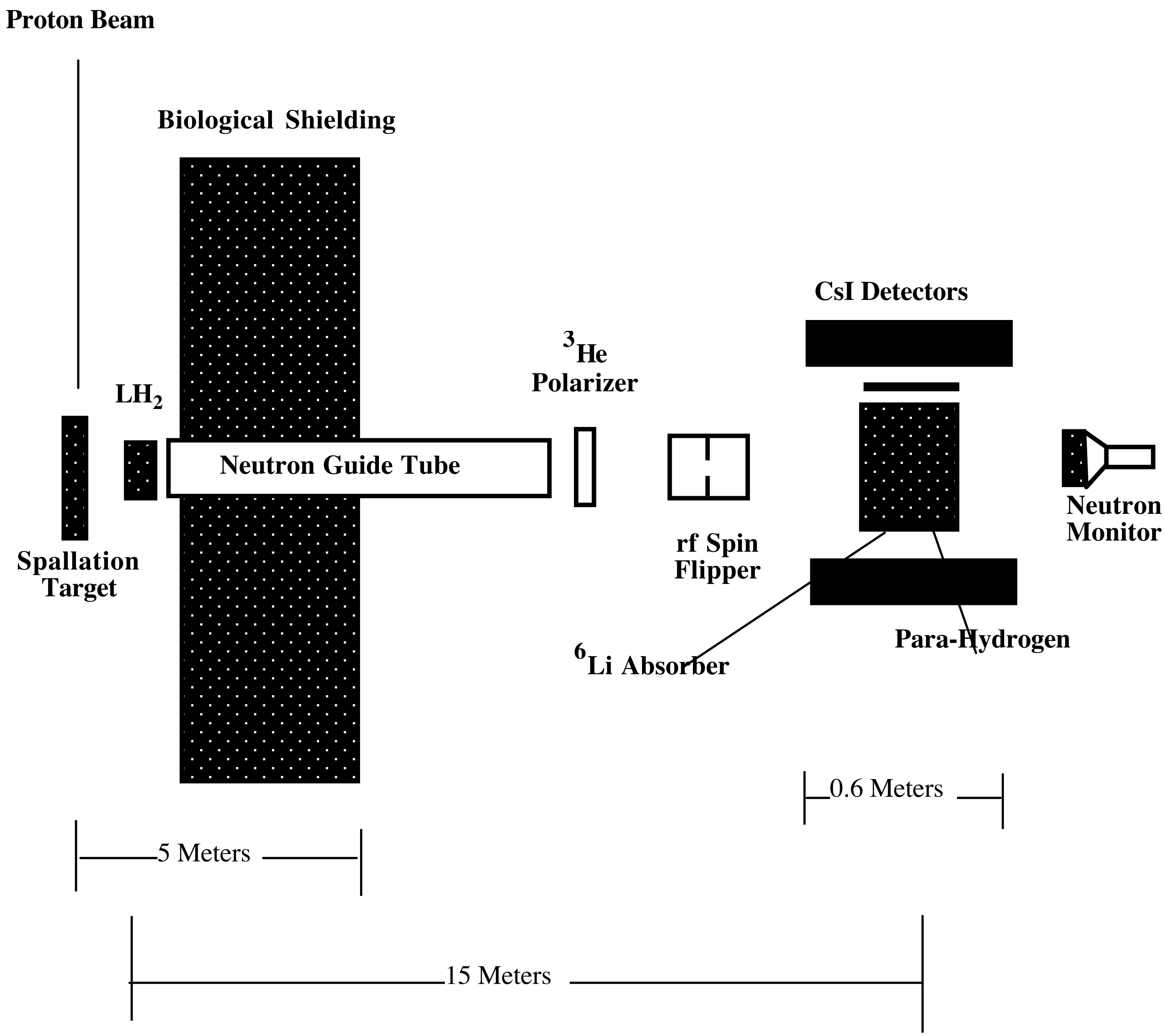
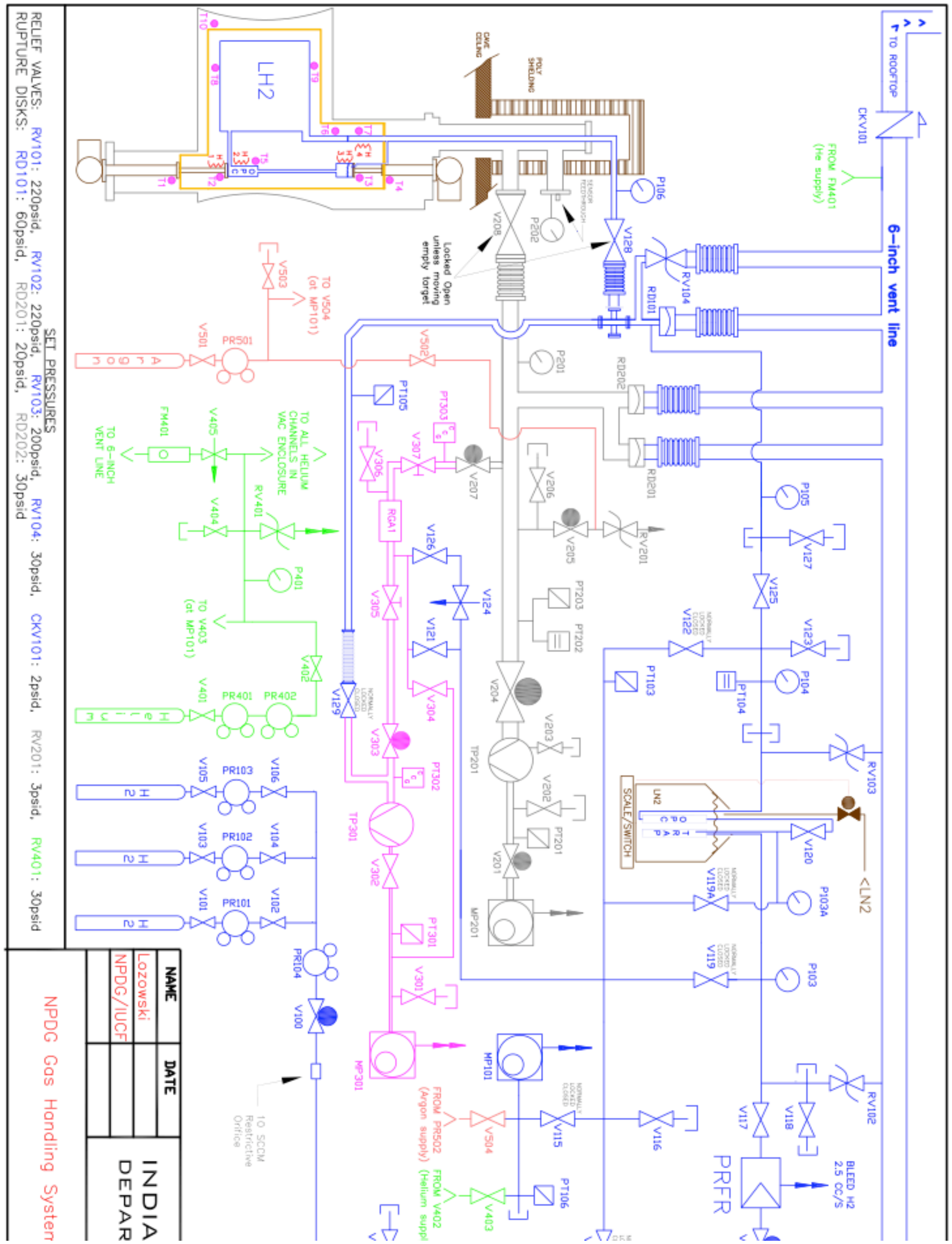

Proton Beam
Biological Shielding
CsI Detectors
3He
Polarizer
LH2
Neutron Guide Tube
Neutron
Monitor
rf Spin
Flipper
Spallation
Target
6Li Absorber
Para-Hydrogen
0.6 Meters
5 Meters
15 Meters

Figure 2: Conceptual Design of NPDGamma Experiment, side view. This document concerns the liquid parahydrogen target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RELIEF VALVES: RV101: 220psid, RV102: 220psid, RV103: 200psid, RV104: 30psid, CKV101: 2psid, RV201: 3psid, RV401: 30psid
RUPTURE DISKS: RD101: 60psid, RD201: 20psid, RD202: 30psid
LH2
6-inch vent line
TO ROOFTOP
CKV101
FROM FM401 (He supply)
Locked Open unless moving empty target
TO ALL HELIUM CHANNELS IN VAC ENCLOSURE
TO 6-INCH VENT LINE
SCALE/SWITCH
BLEED H2 2.5 CC/S
PRFR
FROM PR502 (Argon supply)
FROM V402 (Helium supply)
NAME
DATE
Lozowski
NPDG/IUCF

Figure 2: LH2 Target and Gas Handling System, overall design.

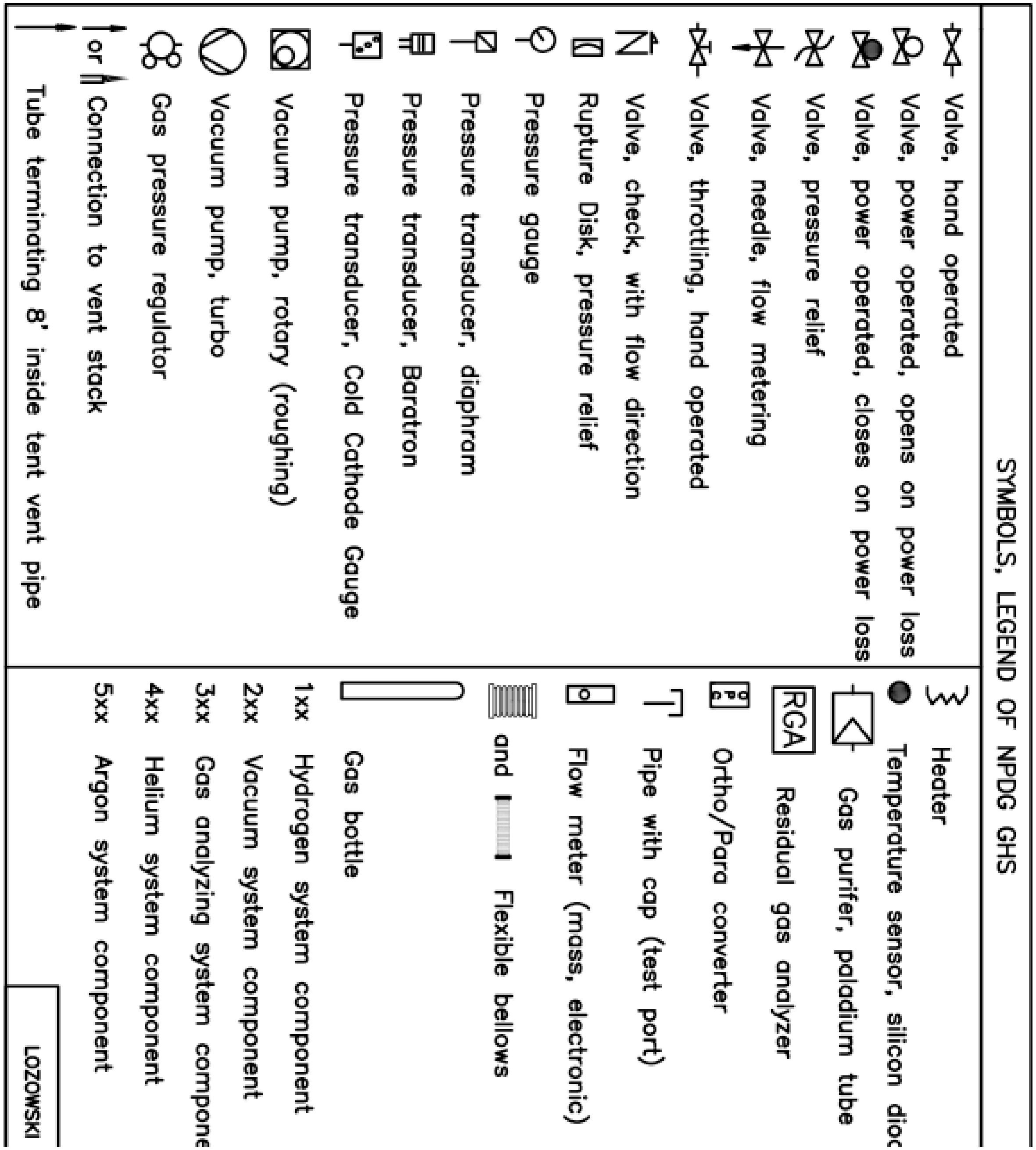

SYMBOLS, LEGEND OF NPDG GHS
Valve, hand operated
Valve, power operated, opens on power loss
Valve, power operated, closes on power loss
Valve, pressure relief
Valve, needle, flow metering
Valve, throttling, hand operated
Valve, check, with flow direction
Rupture Disk, pressure relief
Pressure gauge
Pressure transducer, diaphram
Pressure transducer, Baratron
Pressure transducer, Cold Cathode Gauge
Vacuum pump, rotary (roughing)
Vacuum pump, turbo
Gas pressure regulator
or Connection to vent stack
Tube terminating 8' inside tent vent pipe
Heater
Temperature sensor, silicon dioc
Gas purifer, paladium tube
RGA
Residual gas analyzer
Ortho/Para converter
Pipe with cap (test port)
Flow meter (mass, electronic)
and Flexible bellows
Gas bottle
1xx Hydrogen system component
2xx Vacuum system component
3xx Gas analyzing system compone
4xx Helium system component
5xx Argon system component
LOZOWSKI

Figure 3: Legend for gas handling system shown in Figure 2

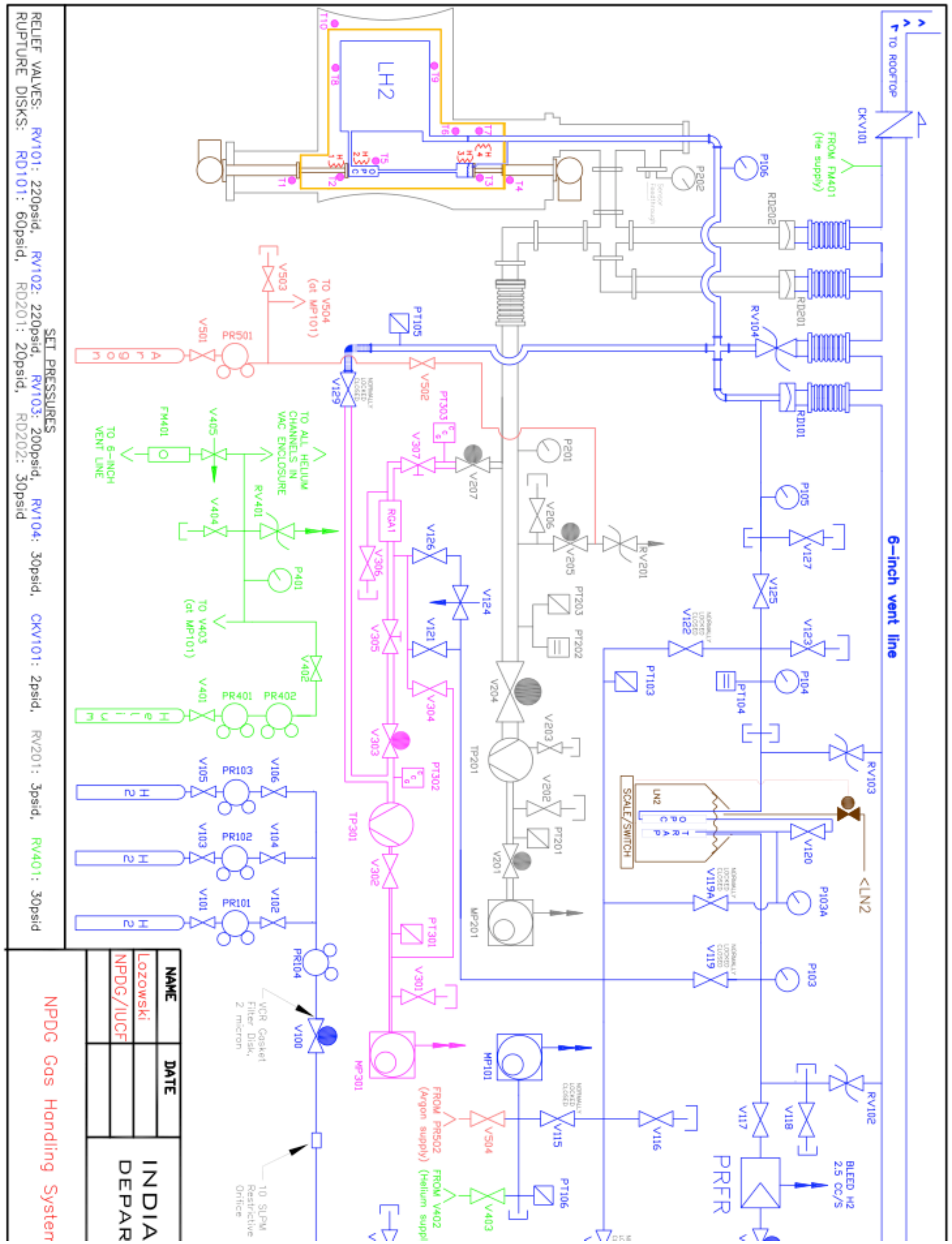

SET PRESSURES
RELIEF VALVES: RV101: 220psid, RV102: 220psid, RV103: 200psid, RV104: 30psid, CKV101: 2psid, RV201: 3psid, RV401: 30psid
RUPTURE DISKS: RD101: 60psid, RD201: 20psid, RD202: 30psid
LH2
6-inch vent line
TO ROOFTOP
NAME
DATE
Lozowski
NPDG/IUCF
PRFR

Figure 4: Overall design of the gas handling system to be used in the shed outside of ER-2 for preliminary tests.

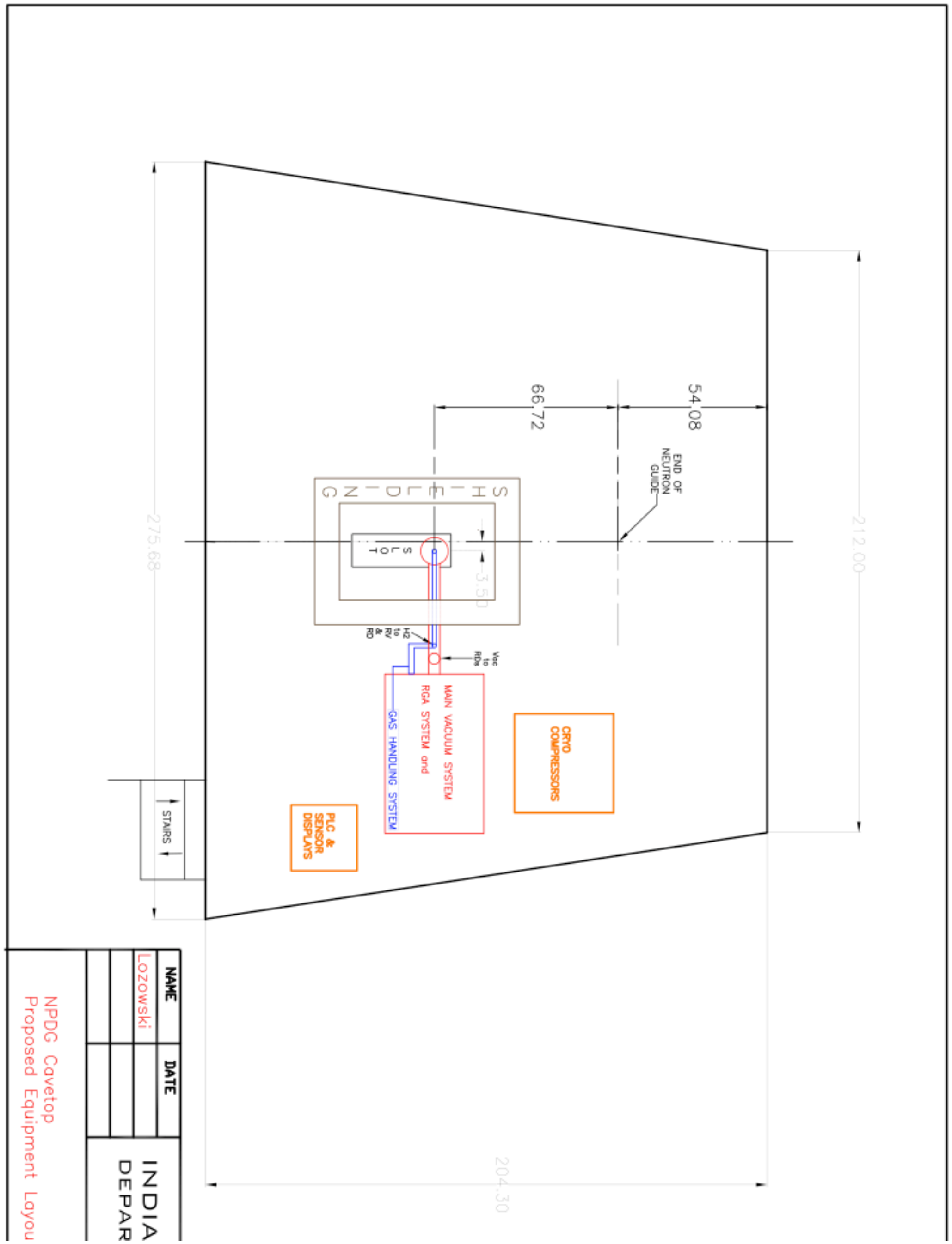

66.72
54.08
END OF NEUTRON GUIDE
SHIELDING
SLOT
3.50
275.68
212.00
H2 to RV & RD
Vac to RDs
MAIN VACUUM SYSTEM
RGA SYSTEM and
GAS HANDLING SYSTEM
CRYO COMPRESSORS
PLC & SENSOR DISPLAYS
STAIRS
204.30
NAME
DATE
Lozowski
INDIA
DEPAR
NPDG Cavetop
Proposed Equipment Layou

Figure 4: a top view of the proposed location of the gas handling system, refrigerator compressors, and SLC system on top of the FP12 experimental cave

A LH_2 Target for NPDGamma (M. Snow, 6-20-01)

We begin with a brief description of the physics goals of the experiment. The goal of this experiment is to search for a parity violating asymmetry in the angular distribution from polarized cold neutron capture on protons with a sensitivity of 5 ppb. To reach this level of statistical accuracy will require operation of the experiment at the LANSCE neutron source for a live time of approximately one year. In addition, we must insure that there exists no other effect in the experiment which introduces an asymmetry in the apparatus which does not come from the reaction of interest. Our goal is to limit the size of all such possible "false" effects to a size of 0.1 ppb. A detailed description of the means by which the overall experiment plans to achieve these goals is included in the DOE proposal. This and other documents relevant to the physics goals of the experiment and the current status of progress toward those goals can be found on the website http://p23.lanl.gov/len/npdg/.

Design goals for the target (M. Snow, 6-20-01, modified 8-20-02 by WMS)

The physics goals of the experiment coupled with the known properties of cold neutron and MeV gamma interactions with materials, the properties of hydrogen, and the need for the target system to be consistent with the other subsystems of the experiment implicitly define the following design goals for the target:

(1) The target must absorb as much of the polarized cold neutron beam flux as possible without depolarizing the neutron beam before capture. The need to prevent neutron depolarization requires the target to consist of parahydrogen at a temperature no higher than 17 K. Given the 10 cm x 10 cm size of the beam at LANSCE, the phase space of the beam from the LANSCE cold neutron guide using 3m supermirror neutron guides, and the scattering cross section of cold neutrons in parahydrogen, the target size of 30 cm diameter and 30 cm length has been chosen on the basis of Monte Carlo simulations using MCNP and the LANL hydrogen neutron scattering kernel. This target will absorb 60% of the incident cold neutron flux. The target system therefore requires a cryostat to liquefy gaseous hydrogen at room temperature and an ortho-para converter to catalyze the formation of parahydrogen.

(2) The target must possess negligible attenuation for the 2.2-MeV gammas from neutron capture. This requires the use of low Z materials in the target vessel and associated radiation shields as well as the vacuum vessel.

(3) To ensure that the statistical accuracy of the measurement is not compromised by extra noise due to density fluctuations in the target, we require a liquid target in which bubbles are suppressed to acceptable levels and in which fluctuations in the pressure and temperature of the target are held to acceptable levels. The suppression of bubbles will be insured by the following design features: (a) the use of a second cryorefrigerator which will be capable of cooling the radiation shield surrounding the target vessel to a temperature below 17 K, thereby reducing the heat load on the 17 K target vessel, and (b) the use of a heater on the exhaust line of the target which can maintain the pressure in the (recirculating) target chamber at a value above that of the equilibrium vapor pressure at 17 K (in other words, the target is superheated

(4) To ensure that no false effects are introduced by gammas produced by polarized slow neutron capture on target materials other than parahydrogen, we must select the target vessel material carefully. The window materials seen by the incoming neutron beam will consist of either Ti or AL alloy on the target vessel itself (vessels made of both materials have been constructed). The remainder of the target chamber, although made of Al and Cu, is protected from polarized neutron capture by a ^{6}Li-rich plastic neutron shield outside of the target flask. This shield will possess an exit hole which will be small enough for polarized neutron capture in the Al exit window to produce a negligible systematic effect but large enough to permit efficient monitoring of the neutron beam exiting the target.

(5) To ensure that the interaction of circularly polarized gammas produces negligible systematic effects and that the magnetic field in the target can be maintained with sufficient uniformity, the target materials in the vicinity of the neutron beam must be nonmagnetic. Any magnetic components in the target system must result in negligible magnetic field gradients.

Responsibilities (M. Snow, 6-20-01)

The target will be designed, constructed, and operated jointly by NPDG collaborators from Indiana University and Los Alamos. The details of the division of responsibilities are discussed in a Memorandum of Understanding (MOU) which is included in the Appendix. Roughly speaking, Indiana University has the major responsibility for target design, construction, and non-LH_2 testing at Indiana and LANL has the main responsibility for target safety and the integration and final testing of the system at LANL.

Target System Design (M. Snow, M. Gericke, H. Nann, 6-20-01, modified 9-13-02 by WMS)

Here we describe the overall design of the target system, including important parameters when required but not including the detailed design calculations which are outlined later in the document in selected cases. We will organize the discussion by following the hydrogen during the filling process. We will restrict our description to the filling procedure and steady state operation of the target with some general comments on the main safety features. Refer to Fig. 1.

The hydrogen starts from a 2000 psi compressed gas cylinder with an ortho-para ratio appropriate to room temperature in thermodynamic equilibrium (3:1). This cylinder will be located outside of the experimental building ER2. The gas will exit through a gas pressure regulator and an automatic valve, which will close in the event of an appropriate warning signal. The fill line will be conducted into the experimental hall and connect to a gas handling system (GHS) located close to the experimental cave. The hydrogen will pass through a particulate filter, a liquid nitrogen trap to remove water and other contaminants, a gas purifier to reduce the concentration of gases other than hydrogen to ppb levels, and an ortho-para conversion chamber based on either chromic oxide (CrO_3) powder or ferric oxide powder and operated at 77K for partial conversion of the gas before entering the refrigerator. All of the modules associated with cleaning and converting the gas can be isolated with manual valves for necessary activation (which typically involving some combination of baking and a pump/purge cycle). The gas flow rate, which is determined by the cooling power of the refrigerators and the properties of hydrogen (see below), will be 10 standard liters/minute.

In addition to the hydrogen line, the gas handling system will also possess two other lines connected to the target system: a main vacuum line for evacuation of the system and a helium gas line to surround all vacuum seals and weld joints, leak test all vacuum components, and flush the system before cool-down. A residual gas analyzer (RGA) on the gas handling system will be used to to act as a helium leak detector during target testing prior to cooling, and to sample the main vacuum gas composition for helium, hydrogen, and other gases during operation. Pressure gauges on the gas handling system will monitor the pressure in the target, helium jacketing, and main vacuum. An electrical feed-through on the gas handling system will provide signals from all thermometers in the target. All transducer signals from the target possess wiring that is located in the main vacuum chamber. Turbopumps on the gas handling system will be used to evacuate the target chambers. The pumps will be isolated from the target vacuum with an automatic valve during filling and manually during steady-state operation to prevent loss of vacuum to the target during a power failure. The plumbing on the gas handling system will consist of welded components and VCR-based joints constructed to typical (10E-9 atm*cc/sec) helium leak tight specifications. Blowoff and vent valves will be present at all required locations. A fill line with Argon gas from a supply bottle will be introduced into the main vacuum system from the GHS when fast warmup of the target is required for emergency response (fire etc.). Plumbing lines entering the target will possess ceramic sections for electrical isolation if necessary and flexible tubing for connection to the target fill-vent stack which extends through the top of the experimental cave. The GHS will be surrounded by a tent with its own vent stack designed in consultation with appropriate LANL staff.

The cooled and preconverted hydrogen gas enters the experimental cave through a reentrant hole in the shielding. It passes vertically into the main vacuum and is thermally connected to the cooling stages of a pulse-tube cryorefrigerator (Cryomech) where the hydrogen is liquified. It then passes into the ortho-para converter chamber which is thermally connected to a mechanical refrigerator (CVI) before entering the target vessel. The refrigerators are located inside the cave and their associated compressors are located outside the cave. The cooling powers of the refrigerators suffice to liquefy the hydrogen and perform the ortho-para conversion for the given flow rate (calculation below). Gas produced by the heat of conversion during filling is recondensed in the ortho-para and liquification chamber and gas produced by boiloff in the chamber recirculates until essentially all (99.8% at 20 K) of the liquid in the target is converted to the para state.

The main vacuum system is constructed entirely of 6061-T6 aluminum by an IU contractor (Ability Engineering). It possesses a horizontal cylindrical region which inserts into the CsI gamma detector array and a downstream rectangular cross-section box whose downstream wall is removeable with an o-ring seal and nonmagnetic Helicoil inserts to avoid galling of the aluminum threads. The rectangular portion is machined out of a solid block of aluminum and the cylindrical portion is cut from extruded pipe to minimize the required amount of weld joints. The entrance and exit windows, two on each side, are formed into a concave shape for increased strength. Two sets of windows exist: one made of 6061-T6 aluminum alloy and the other made of magnesium alloy (Ability Engineeering). Helium gas is introduced into the space between the windows, into gas channels machined into the chamber and introduced using pipe threaded holes, and in the space between the inner and outer o-ring seals in such a way that every seal and weld joint is exposed to helium gas to catch any leaks into the vacuum system. To prevent helium diffusion through the viton o-ring seals the inner seal is made with indium wire. The top of the chamber possesses threaded holes for lifting eye-bolts. The inside surface of the chamber and the inside surfaces of the windows are polished to a mirror finish to reduce emissivity.

The liquid parahydrogen flows down a narrow fill line into the bottom of a 20-liter cylindrical target chamber. The chamber is wrapped with 6Li-rich flexible plastic neutron shielding (~2mm), a thin copper shield, and superinsulation (Mylar coated with aluminum on both sides with adjacent layers separated by polyethylene netting) and is supported and separated from the 80K copper radiation shield by a thermally-insulating support structure made of a G-10 ring. Thermal connection of both refrigerators to the target chamber, ortho-para converter, and radiation shields is effected by both mechanical connection to the cold stage flanges, a thick copper bar and clamps on the rear of the vessel and along the exhaust line, and, where necessary, by flexible copper braid. A similar G-10 support structure separates the 80K radiation shield from the inside of the main vacuum chamber. This support structure allows the liquid target chamber to slide horizontally upon thermal contraction. Stress on the target from differential thermal contraction in the vertical direction is accommodated with the use of a curved fill line on the inlet and a formed stainless bellows on the outlet line of the target. Stress on the 80K radiation shield due to differential thermal contraction in the vertical direction is accommodated by the flexibility of the thin walls of the radiation shields introduced by cutting radial slots into the soft copper sheet near the thermal contact to the lower (CVI) refrigerator. The inlet and outlet lines of the target are bent to avoid excessive radiative heat loads from a line-of-sight view of a room temperature surface.

The titanium (Excelco) and aluminum (Ability Engineering) target chambers are identical in design. They are both welded pressure vessels with two weld seams, one at the convex entrance dome and the other at the concave exit dome, that have been pressure tested, helium leak tested, and thermally shocked by dunking into liquid nitrogen. The vessel design was arrived at through finite element calculations performed by the ARES corporation, a LANL contractor. There are two Conflat vacuum flanges on the target chamber on the inlet and outlet lines. The seals for each of these lines have successfully been thermally cycled several times to liquid nitrogen temperature without leaks. The inner surface of the titanium vessel was treated to ensure that a sufficiently-thick oxide layer exists to reduce any possible embrittlement of the titanium to negligible levels and tests were conducted on separate titanium test pieces treated in the same manner to ensure that the treatment did not reduce the yield strength of the titanium alloy used. The target chamber includes a cylindrical neutron shield loaded with ^{6}Li to prevent polarized neutron capture on the Al target vessel with a 10 cm x 10 cm entrance hole for the neutron beam and a much smaller exit hole for monitoring purposes downstream of the target. Given the cooling powers stated above and the known thermodynamic properties of hydrogen, we estimate a filling time for the target of about 2 days.

The exhaust line from the liquid hydrogen vessel possesses a large inner diameter (1.5”). This exhaust line passes through a flange on the main vacuum system and to the outside of the cave, where it is connected to a main exhaust line that vents to a location outside the ER2 building on the roof. The diameter of this line has been determined by a series of calculations outlined below to insure that there is no release of liquid hydrogen in the event of a loss of vacuum. These calculations were verified in test measurements performed at Indiana in April 2003 and are described below. In addition, the main vacuum also possesses a similar vent line (2.5” diameter) which ensures that there is no release of hydrogen in the event of a rupture of the target.

The liquid fills the target chamber and also a portion of the exhaust line. The exhaust line is thermally isolated from the target vessel with a section of tubing made of nonmagnetic stainless steel. This section of the exhaust line contains a heater, which is used to locally heat the liquid. Due to the low thermal conductivity of the liquid parahydrogen and the tubing, it is possible to maintain a small temperature gradient in the liquid in the exhaust line. The heater performs two functions: (1) it maintains the gas pressure in the target chamber at a value higher than the equilibrium vapor pressure of the liquid seen by the neutron beam, thereby superheating the target and suppressing bubble formation, and (2) it induces the circulation of hydrogen through the target through a small-diameter connection which reintroduces the evaporated gas back into the target fill line and back through the liquifoer and the ortho-para converter. In this way when the target is full and in steady-state operation, it is bubble-free and continuously reconverted to liquid parahydrogen.

During the filling of the LH2 system and during steady-state operation the hydrogen pressure will be maintained above 15 psia, which is comfortably above the local atmospheric pressure at Los Alamos as required by the safety committee. When the target is operating in steady-state mode most of the GHP will be valved off except for the blowoff valves and the residual gas analyzer.
The thermodynamic state of the target is determined using pressure and temperature measurements on the target, cryorefrigerators, ortho-para converter, and exhaust line.

The voltages from the thermometers are read by commercial temperature monitors (Lakeshore and Scientific Instruments) which also produce the feedback power to the refrigerators to control the temperatures. This information, along with pressures, the status of automatic valves on the GHS, and the information from the RGA, is fed into a SLC-based control system (Allen-Bradley) whose function is to monitor the status of the target, to take appropriate action if any measured parameters are out-of-range, to record and display the history of these parameters, to communicate the status of the target to appropriate LANL areas, and to present the status of the target visually to operators using a convenient front-panel display.

Main Safety Aspects of the Design (M. Snow, H. Nann, 6-20-01, modified 3-6-03 by WMS)

The size of the liquid hydrogen target (approximately 21 liters) coupled with its location in a confined space during the experiment (a cave for neutron and gamma shielding), the need for access in the cave while the target is full, and the presence of several electrical systems inside the cave in other parts of the apparatus, dictate certain safety requirements. A preliminary assessment of the safety requirements for this target was performed in 1999 at LANL. The Appendix contains the report of this safety assessment and recommendations of the committee, which evaluated a preliminary conceptual design of the target. Because of the preliminary nature of the design at that time, certain details of the recommendations of the committee are no longer relevant to the current design. The next safety review, which was held at Indiana University in the fall of 2001, evaluated a much more mature version of the design. The Appendix also contains the report and recommendations from this meeting. The main recommendations of the 1999 safety committee were as follows:

(1) The target must be designed so that no release of hydrogen into the experimental cave occurs in the event of either a failure of the main vacuum system or a failure of the target vessel.

(2) All parts of the target vacuum system inside the cave must be surrounded by a helium jacket.

NOTE: The second condition was later clarified in a request to the safety committee to apply to only the weld joints and the o-ring seals in the parts of the target system inside the cave. The point is that parts of the solid walls of the main vacuum unmodified from the state as supplied by the manufacturers will not spontaneously develop leaks in the absence of gross chemical of physical assaults on the material. Therefore it is not necessary to surround the outside surfaces of the unwelded portions of the main vacuum system with helium gas. The main vacuum system was therefore designed with internal channels and double-walled windows in such a way that the outside surfaces of all o-ring seals and weld joints are surrounded with helium. The exchange with the safety committee detailing these arguments is included in the Appendix.

Recommendation (1) and the modified form of (2) have been incorporated into the target system. Here we summarize the results of our analysis of the most serious safety issue: response of the system to catastrophic vacuum or target failure. Details of the calculations are included.

Hydrogen-air mixtures in concentrations ranging from 4% to 75% of H_2 by volume are highly explosive. Normally a spark of some kind is needed for ignition, but hydrogen vapor escaping from leaks has been known to spontaneously combust. It is, therefore, of paramount importance to eliminate the possibility of explosive hydrogen-air mixtures occurring and to prevent ignition. The mechanical aspects of the liquid hydrogen (LH_2) target system are designed to minimize the possibility of a hydrogen release into the experimental cave and hall in case of a leak or rupture due to overpressure. A control system is developed to allow the careful monitoring of the target system behavior and to respond to any aberration from normal operating conditions.

The liquid hydrogen target system consists of three components ("triple containment"). The LH_2 target flask (first containment) connected to the condenser unit by a filling and a vapor escape line is contained inside a vacuum vessel, (second containment) which provides thermal insulation together with the 80K radiation shield. Helium jacketing (third containment) surrounds the weld joints and o-ring seals in the vacuum vessel and the hydrogen piping system to the outside of the experimental cave. This helium jacketing has a dual purpose. First, if a leak occurs in a weld joint or seal in the vacuum vessel, it can be detected immediately by a RGA monitoring the vacuum. Second, the helium jacket prevents air or other gases from penetrating into the vacuum through such leaks. If gases other than helium (and hydrogen) get in contact with the LH_2 flask or the hydrogen piping from the refrigerators to the target, they will immediately freeze. Solidified gases are difficult to detect, as they will not produce a pressure increase. Solid oxygen and nitrogen may radiolyse in the radiation field around the LH_2 target and form compounds that can self-ignite.

There are several maximum credible accidents possible.

(1) A loss of either refrigeration or vacuum will lead to a rapid boiling in the target flask and cause the pressure in the condenser-target system to rise. In the case of overpressure buildup, a pressure relief system, consisting of a safety relief valve and a rupture disc in parallel, will release the hydrogen gas into a vent line that exhausts through the roof of the ER2 building high up into the outside atmosphere. This vent line is a 6-inch diameter, 304 or 304L stainless steel tube closed toward the outside atmosphere by a leak tight check valve and filled with helium at 1 atm.

(2) A rupture of the target flask or piping inside the vacuum vessel will release the LH_2 into the vacuum and hydrogen will boil off. Again when overpressure through the rapid boil off occurs, a pressure relief system will safely release the hydrogen gas into the vent line and the outside of the building while maintaining the pressure within the target vessel at a safe level. It should be mentioned that during normal operation the vacuum pump is isolated from the vacuum vessel.

(3) In case of fire in the experimental area or for some other reasons, the LH_2 in the target flask has to be disposed off very quickly. This will be done by filling the vacuum vessel with argon thus letting the LH_2 boil off at a controlled rate. This scenario is similar to the one described under (1) above, but with more heat flowing into the target flask.

Each of the components of the LH_2 target system has a separate pressure relief system, which is sufficiently robust to respond safely to any maximum credible accident. The conductance of each safety relief system has to be large enough that a pressure rise will not lead to a rupture of the component. Calculations based on the Bates Internal Report # 90-02 [21] and the Crane Technical Paper No. 410 [11] were performed to determine the size of the relief plumbing such that the mass flow remains subsonic at all times and that the maximum pressure in each component remains well below its bursting point. The final results show that, in the case of a catastrophic vacuum failure to air, the target flask is subjected to a pressure of no more than 47 psia if the inner diameter of the pressure relief piping is 1.5 inch, assuming a boiloff rate of 0.20 lb/s. The maximum pressure in the vacuum vessel for the case of a rupture of the target flask is 43 psia for an inner diameter of the pressure relief piping is 2.5 inch and a boiloff rate of 0.50 lb/s. Both pressures are well below the 90 psia pressures that the target flask and vacuum vessel will be tested at. These estimates were confirmed by measurements at Indiana which used nitrogen as the working fluid in the target vessel along with the appropriate scaling of the results for the thermodynamic differences between liquid nitrogen and liquid hydrogen.

In summary, pressure relief systems with a 1.5-inch inner diameter discharge pipe for the target flask and a 2.5-inch inner diameter discharge pipe for the vacuum vessel will respond safely to catastrophic failures.

Various gas monitoring systems must be active to ensure that an explosive mixture does not occur in the first place. We propose to monitor the vacuum space for hydrogen, helium, and oxygen with a RGA. We believe (and the safety committee in its second report concurs) that there is no need to monitor the helium jacket for hydrogen, since hydrogen will be detected in the main vacuum long before it is seen in the helium jacket.

Quality Management Plan

- **Quality Assurance Plan**
- **Change Control (3-9-03 WMS)**

The second safety meeting defined a change control process by which formal requests for changes in the baseline design presented to the safety committee could be forwarded to the committee for response. We enclose in the Appendix the subject matter contained in these change control requests along with the response of the committee through J. Knudson, head of the committee.
The changes to the design approved through the change control process were (1) the approval of the potential use of titanium as a target vessel material, (2) the redefinition of the areas requiring external helium atmosphere to the weld joints and o-ring seals and the subsequent redesign of the vacuum system to incorporate internal channels for the introduction of the helium in the needed locations, (3) approval of the use of the Cryomech pulse tube cryorefrigerator for one of the mechanical refrigerators, (4) clarification of the nature of the radiography requirements associated with the change in design to incorporate the internal channels for helium conduction.

Design (M. Snow, 8-19-03)

This section consists of a detailed description of the specifications of the NPDGamma liquid hydrogen target system as of August 2003 after the target was moved to LANL from Indiana.

Cryostat and Vessels

- **specifications (M. Snow, 6-15-01, modified 2-21-03 by WMS)**

Table 1 lists the main mechanical specifications of the target vessel, main vacuum, helium jacketing and radiation shields.

Table 1: Specifications of LH2 target, radiation shields, main vacuum, and He jacketing.

Object	Mechanical Properties			Connections
	Dimensions	Material	Fabrication	
LH2 target vessel	30 cm diameter 30 cm length wall thicknesses: cylindrical shell 0.25 cm, entrance window 0.32 cm, exit window 0.38 cm	6061 Al or Ti	Cylindrical Al or Ti body welded from cold-rolled sheet. Rear dome machined from monolithic material	1.2 cm diameter liquid inlet flange, Al Conflat seal 3.8 cm diameter outlet flange, Al Conflat seal
80K Radiation shield	36 cm diameter 80 cm length 0.1 cm thickness	OFHC Cu	Soldered from cold-rolled and annealed sheet	22 cm diameter mechanical connection to refrigerator #1 and 8 cm diameter connection to refrigerator #2
Main Vacuum Vessel	40 cm diameter 98 cm length 0.30 cm thickness	6061 Al body 6061 Al or Mg windows	Cylindrical Al body welded from cold-rolled sheet. Rectangular Al box machined from single Al piece. Inlet and outlet flanges welded. Al/Mg windows formed from plate	2.5 cm diameter flange to external pump and GHP
Helium Gas jacketing			Internal channels machined into Al body of the main vacuum system and appropriate weld joint areas before welding	Pipe-threaded external access holes connected to all internal channels, filled with small connectors and fed by small ID tubing for helium gas connection

Figure 4: Liquid Hydrogen Target Vessel, overall views. The drwwings show the two cryorefrigerators,(one with condensation lines for the hydrogen), the vertical penetration for the fill and vent lines to the outside of the cave, the concave double windows for the entrance and exit of the neutron beam, and the two-part main vacuum chamber with a horizontal cylindrical section that houses the hydrogen target and the box section which contains the refrigerator and feed line penetrations along with a removeable rear flange for access to the rear (downstream of the neutron beam) end of the chamber. The neutron beam enters at the front of the cylindrical section.

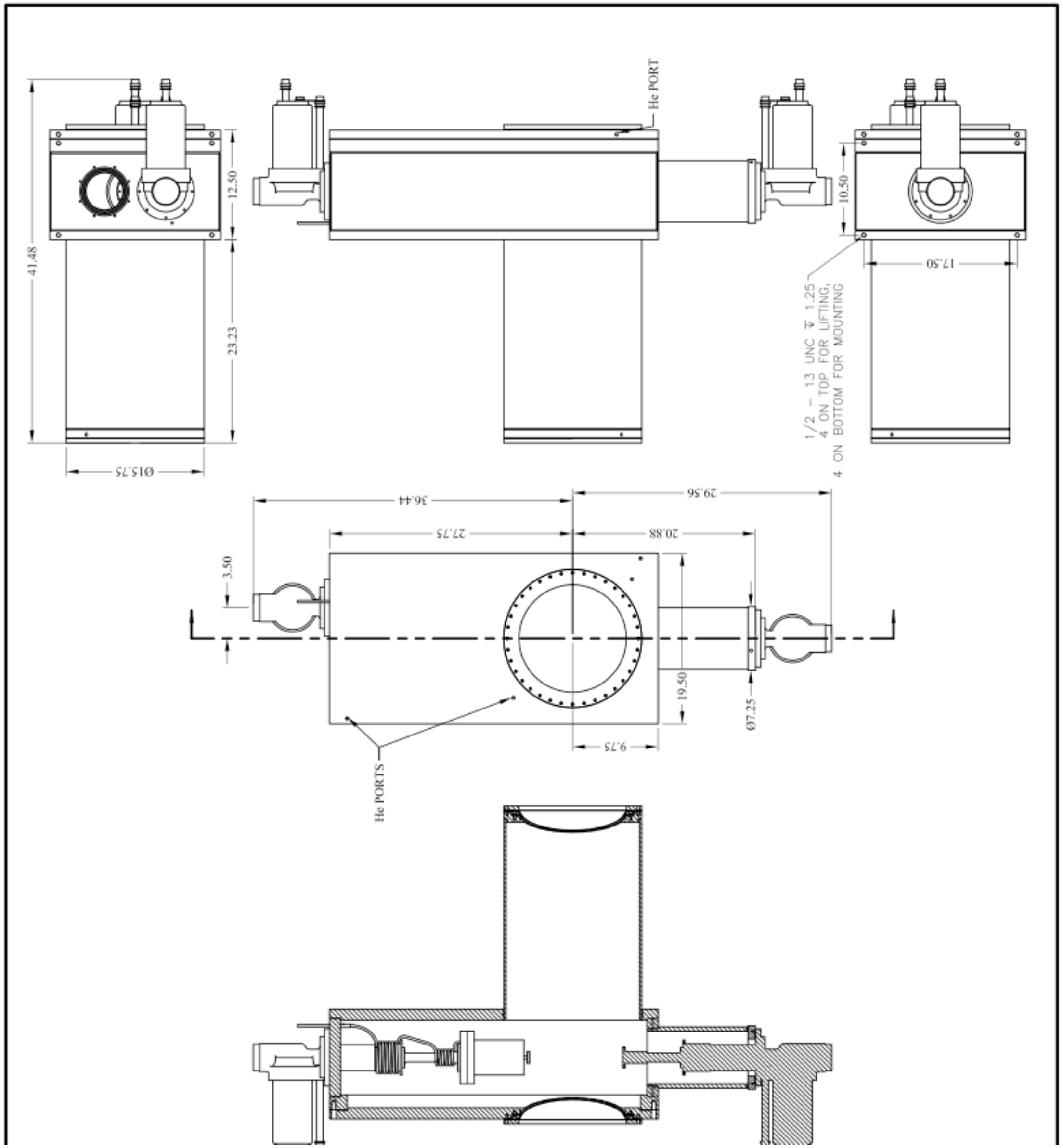
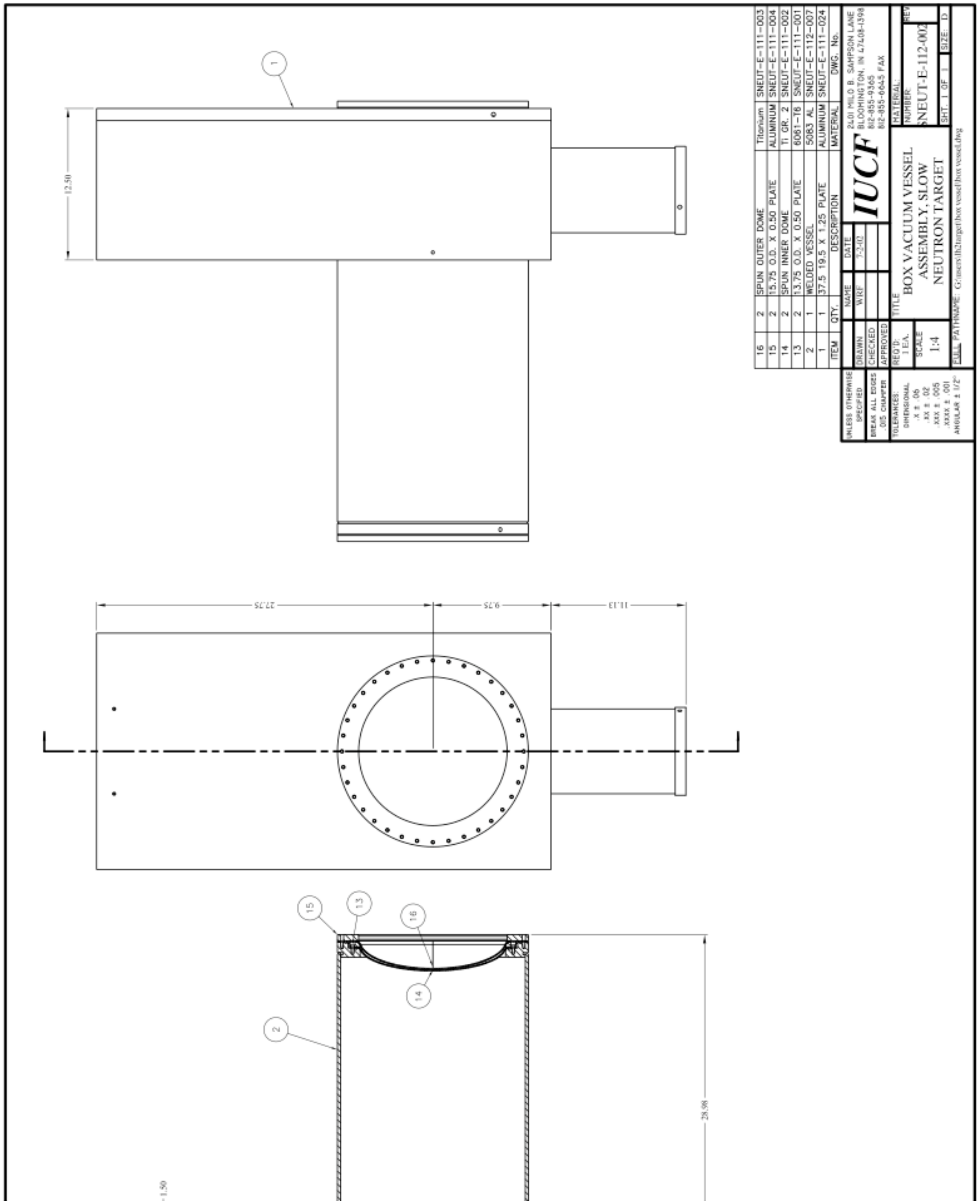

He PORT
41.48
12.50
23.23
Ø15.75
10.50
17.50
1/2 - 13 UNC ∓ 1.25
4 ON TOP FOR LIFTING,
4 ON BOTTOM FOR MOUNTING
36.44
27.75
29.56
20.88
3.50
19.50
Ø7.25
9.75
He PORTS

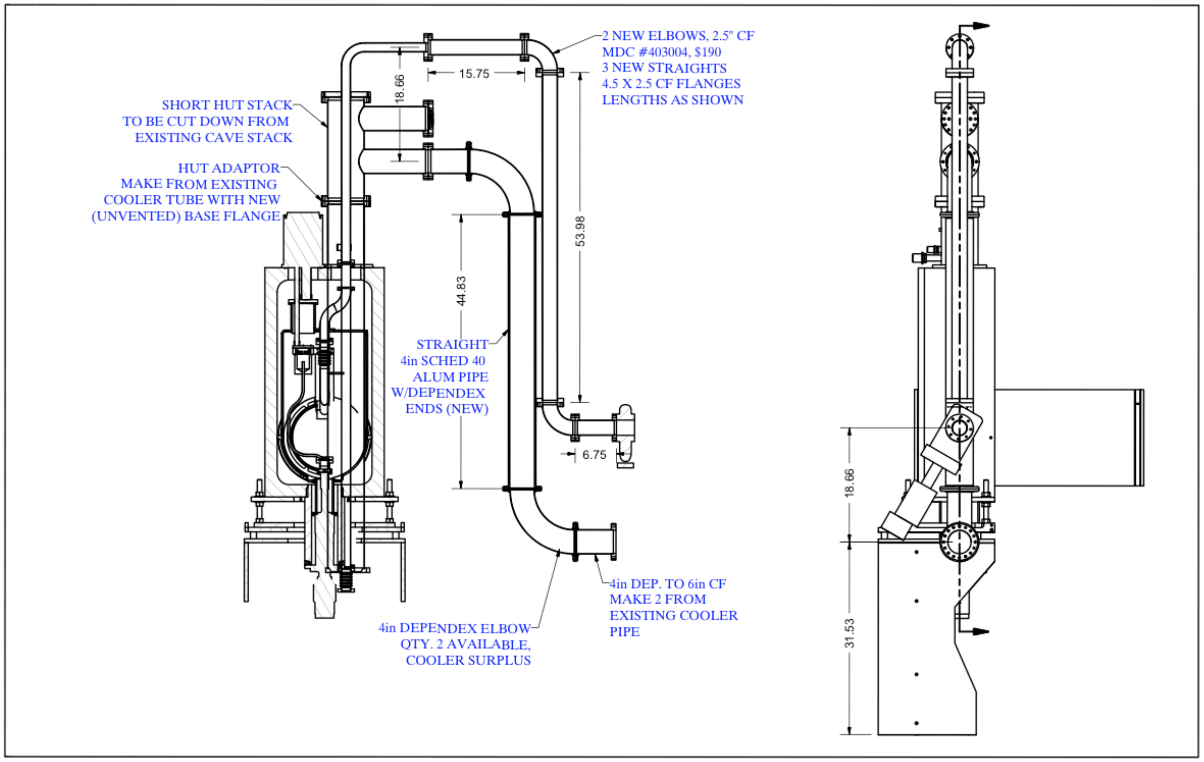
Figure 5:

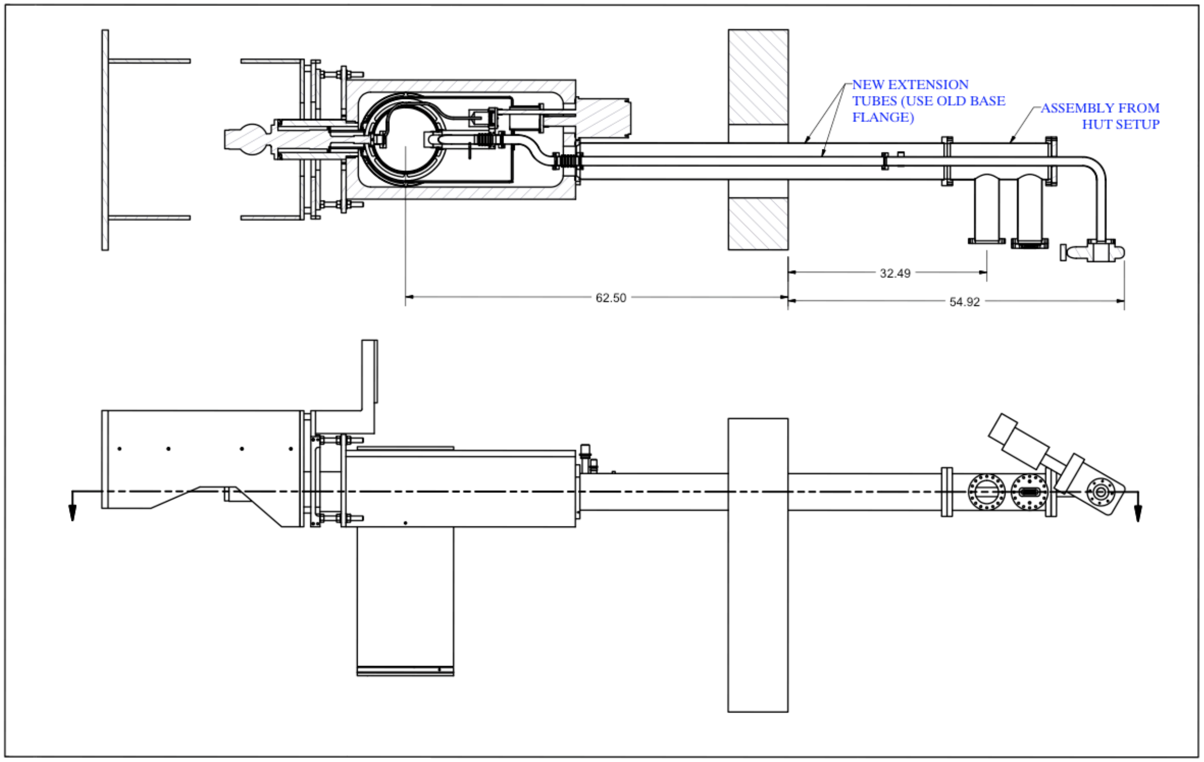
Figure 6: LH_2 Target Main Vacuum Assembly. Shows the thickness of the box section of the vacuum chamber,with the removeable rear section. The main body of the box section of the vacuum chamber was machined from a single ingot of aluminum to minimize weld joints.



IUCF
2401 MILO B. SAMPSON LANE
BLOOMINGTON, IN 47408-1398
BOX VACUUM VESSEL
ASSEMBLY, SLOW
NEUTRON TARGET
SNEUT-E-112-002
16 2 SPUN OUTER DOME Titanium SNEUT-E-111-003
15 2 15.75 O.D. X 0.50 PLATE ALUMINUM SNEUT-E-111-004
14 2 SPUN INNER DOME Ti GR. 2 SNEUT-E-111-002
13 2 13.75 O.D. X 0.50 PLATE 6061-T6 SNEUT-E-111-001
2 1 WELDED VESSEL 5083 AL SNEUT-E-112-007
1 1 37.5 19.5 X 1.25 PLATE ALUMINUM SNEUT-E-111-024
ITEM QTY. DESCRIPTION MATERIAL DWG. No.

Figure 7: Mechanical drawing of the piping system extendinf from the hydrogen target to the gas handling system.





- **Strength Calculations: (H. Nann, 08-10-01)**

The ASME Code, Section VIII, [9] and Cryogenic Process Engineering [13] provide the design equations, which were used to calculate the minimum shell thickness.

List of symbols used in the formulae below:

t = minimum thickness [inch]
p = internal design pressure [psi]
p_c = critical pressure [psi]
R = inside radius [inch]
R_o = outside radius [inch]
D = inside diameter [inch]

D_o = outside diameter [inch]
L = length of cylinder or distance between two stiffening rings, respectively [inch]
S = allowable stress [psi]
Y = modulus of elasticity (Young's modulus)
μ = Poisson's ratio
E = weld joint efficiency factor

(a) Cylindrical shell under internal pressure.

$$t = \frac{pD}{2(SE - 0.6p)} \quad \text{(eq. 1)}$$

(b) Elliptical head under pressure on concave side

$$t = \frac{pDK}{2(SE - 0.1p)} = \frac{pD_0K}{2(SE + pK - 0.1p)} \quad \text{(eq. 2)}$$

where the constant K is given by $K = \frac{1}{6}\left[2 + \left(\frac{D}{2h}\right)^2\right]$ with

$\frac{D}{2h}$ = ratio of the major to the minor axis of elliptical heads

(c) Elliptical head under pressure on convex side

$$t = \left[\frac{2p_c\left[3(1-\mu^2)\right]^{1/2}}{YE}\right]^{1/2} R_0^* \quad \text{(eq. 3)}$$

with $R_0^* = K_1 D_0$.

K_1 is given in table UG–33.1 of the ASME Code as a function of $\frac{D_0}{2h_0}$.

The ASME Code specifies that the critical pressure p_c be four times the allowable (external) working pressure on a vessel.

(d) Cylindrical shell under external pressure

The minimum thickness can be obtained by solving iteratively the relation

$$t = \left[\frac{p_c \left(1 - \mu^2\right)^{3/4} \left[\left(L / D_0\right) - 0.45 \left(t / D_0\right)^{1/2} \right]}{2.42 YE} \right]^{2/5} D_0 \qquad \text{(eq. 4)}$$

The ASME Code specifies that the critical pressure p_c is four times the maximum allowable external working pressure.

The following material constants at room temperature, taken from AMS Handbook, Vol. 2 (Ref. …), are used. The materials have (about 30% – 40%) higher allowable stresses at low temperature.

(a) Aluminum 6061-T66061-T6 (ASME Code approved)

Ultimate tensile strength: S_u = 42000 psi
⇒ allowable stress S = _ S_u = 10500 psi (see ASME Code)

Modulus of elasticity: $Y = 1.0 \times 10^7$ psi

Poisson's ratio: $\mu = 0.33$

(b) Titanium Grade 2, Annealed (ASME Code approved???)

Ultimate tensile strength: S_u = 50000 psi
⇒ allowable stress S = _ S_u = 12500 psi (see ASME Code)

Modulus of elasticity: $Y = 1.45 \times 10^7$ psi

Poisson's ratio: $\mu = 0.34$

(c) Magnesium AZ31B-H24 or AZ31C-H24 alloy, Hard rolled sheet (<u>NOT</u> ASME Code approved!)

Ultimate tensile strength: S_u = 38000 psi
⇒ allowable stress S = _ S_u = 9500 psi (see ASME Code)

Modulus of elasticity: $Y = 6.5 \times 10^6$ psi

Poisson's ratio: $\mu = 0.35$

(A) **LH_2 Target Flask (cylinder with elliptical heads):**

First calculate the minimum wall thickness for an internal design pressure of $p = 75$ psia.
$E = 1.0$ (butt joints with complete penetration, fully radiographed)

(1) Cylindrical shell:

Material: 6061-T66061-T6 Aluminum

$R = 6.0$ inch, $D = 12.0$ inch, $L = 12.0$ inch

$$t = \frac{(75)(12.0)}{2[(10500)(1.0) - (0.6)(75)]} = 0.043 \text{ inch}$$

(2) Entrance window, elliptical head, machined from one piece, pressure on concave side:

Material: Magnesium alloy AZ31B-H24

$D = 10.5$ inch
$h = 2.3$ inch

$$\frac{D}{2h} = 2.3 \quad \Rightarrow \quad K = 1.21$$

$$t = \frac{(75)(9.5)(1.21)}{2[(9500)(1.0) - (0.1)(75)]} = 0.045 \text{ inch}$$

(3) Exit window, elliptical head, pressure on convex side:

Material: 6061-T66061-T6 Aluminum

$D_o = 8.75$ inch
$h_o = 1.90$ inch

$$\frac{D_0}{2h_0} = 2.3 \quad \Rightarrow \quad K_1 = 1.03 \quad \Rightarrow \quad R_0^* = 9.01 \text{ inch}$$

assume $p_c = 4(45)$ psi = 180 psi

$$t = \left[\frac{(2)(180)\left[3\left(1-0.35^2\right)\right]^{0.5}}{1.0\times 10^7}\right]^{0.5}(9.01) = 0.069 \text{ inch}$$

CONCLUSION: To provide a factor of safety, we will use $t = 0.1$ inch for the thickness of the cylindrical part, $t = 0.125$ inch for the entrance window, and $t = 0.15$ inch for the exit window.
Now insert these thicknesses into the above formulae. Assuming a welding efficiency of 0.9 (except for the entrance window, which contains no welds), we obtain for the *maximum allowable internal working pressures*:

(1) Cylindrical shell: $p_{int} = 159$ psia
(2) Entrance window: $p_{int} = 168$ psia
(3) Exit window: $p_{int} = \_\, p_c = 190$ psia

and for the *maximum allowable external working pressures*:

(1) Cylindrical shell: $p_{ext} = \_\, p_c = 44$ psia
(2) Entrance window: $p_{ext} = \_\, p_c = 67$ psia
(3) Exit window: $p_{ext} = 267$ psia

(B) **Vacuum Vessel (cylinder with elliptical heads):**

First calculate the minimum wall thickness for an internal design pressure of $p = 75$ psia since the main concern for the vacuum vessel is that it can withstand the pressure buildup in the case of a rupture of the target flask.
$E = 1.0$ (butt joints with complete penetration, fully radiographed)

(1) Cylindrical shell:

Material: 6061-T6 Aluminum

$R = 8.0$ inch, $D = 16.0$ inch, $L = 37.0$ inch

$$t = \frac{(75)(16.0)}{2[(10500)(1.0) - (0.6)(75)]} = 0.057 \text{ inch}$$

(2) Entrance window, elliptical head, pressure on convex side:

Material: Titanium Grade 2, Annealed

$D_o = 13.5$ inch
$h_o = 2.9$ inch

$\frac{D_0}{2h_0} = 2.3 \quad \Rightarrow \quad K_1 = 1.03 \quad \Rightarrow \quad R_0^* = 13.9$ inch

assume $p_c = 4(45)$ psi $= 180$ psi

$$t = \left[\frac{(2)(180)\left[3\left(1 - 0.34^2\right)\right]^{0.5}}{1.45 \times 10^7}\right]^{0.5}(13.9) = 0.088 \text{ inch}$$

(3) Exit window, elliptical head, pressure on concave side:

Material: 6061-T6 Aluminum

$D = 8.75$ inch
$h = 1.90$ inch

$\frac{D}{2h} = 2.3 \quad \Rightarrow \quad K = 1.21$

$$t = \frac{(75)(16.0)(1.21)}{2[(10500)(1.0) - (0.1)(75)]} = 0.069 \text{ inch}$$

Conclusion: To provide a factor of safety, we use a wall thickness $t = 0.12$ inch for the cylindrical shell and the elliptical heads.

Now calculate whether the target vessel can withstand an external pressure of 18 psia . $\Rightarrow$ $p_c = 4(18\text{psia}) = 72$ psia

(1) Cylindrical shell under external pressure

Assume no stiffening ring except the two flanges at the ends, which act as stiffening rings.

$L = 37$ inch, $D_o = 16.0$ inch, $t = 0.12$ inch

$$\frac{L}{D_0} = 2.31 \qquad \frac{t}{D_0} = 0.0075$$

The *RHS* of eq. (4) is

$$RHS = \left[\frac{(72)\left(1-0.33^2\right)^{0.75}\left\{2.31-0.45(0.0075)^{0.5}\right\}}{2.42\left(1.0\times 10^7\right)(1.0)}\right]^{0.4}(16.0) = 0.13 \text{ inch}$$

This value is larger than the assumed thickness of 0.12 inch. Thus a stiffening ring at the middle of the cylinder is required.

Now L becomes the distance between the stiffening rings. $\Rightarrow$ $L = 18.5$ inch

$$\frac{L}{D_0} = 1.156$$

The *RHS* of eq. (4) is now

$$RHS = \left[\frac{(72)\left(1-0.33^2\right)^{0.75}\left\{1.156-0.45(0.0075)^{0.5}\right\}}{2.42\left(1.0\times 10^7\right)(1.0)}\right]^{0.4}(16.0) = 0.10 \text{ inch}$$

This value is smaller than the assumed thickness. Thus a cylindrical vacuum vessel with a wall thickness of 0.12 inch and stiffening rings at the middle and two ends will be sufficient to keep it from collapsing due to a pressure of 18 psi on the outside.

(2) Entrance head, pressure on concave side:

$$\frac{D}{2h} = 2.3 \qquad \Rightarrow \qquad K = 1.21$$

$$t = \frac{(18)(16)(1.21)}{2(12500)(1.0)-2(18)(1.21-1)} = 0.014 \text{ inch}$$

This value is smaller than the design thickness of 0.12 inch.

(3) Exit head, pressure on convex side:

$$\frac{D_0}{2h_0} = 2.3 \qquad K_1 = 1.03 \qquad R_0^* = 16.5 \text{ inch}$$

$$t = \left[\frac{(2)(72)\left[3\left(1 - 0.33^2\right)\right]^{0.5}}{1.0 \times 10^7} \right]^{0.5} (15.5) = 0.080 \text{ inch}$$

This value is smaller than the design thickness of 0.12 inch

Conclusion: The vacuum vessel can withstand an external pressure of 18 psig without collapsing.

Using a wall thickness of $t = 0.12$ inch, we obtain for the *maximum allowable internal working pressures*:

(1) Cylindrical shell: $p_{int} = 141$ psia
(2) Entrance window: $p_{int} = \_\ p_c = 83$ psia
(3) Exit window: $p_{int} = 155$ psia

and for the *maximum allowable external working pressures*:

(1) Cylindrical shell: $p_{ext} = \_\ p_c = 29$ psia
(2) Entrance window: $p_{ext} = 163$ psia
(3) Exit window: $p_{ext} = \_\ p_c = 40$ psia

(C) **Rectangular Vacuum Box (H. Nann, 09-06-02)**

The required thickness for unstayed flat heads is calculated by the following formula:

$$t = d\sqrt{\frac{ZCp}{SE} + \frac{6Wh_G}{SELd^2}}$$

with *C = factor depending upon method off attachment of head: C = 0.3*

p = internal design pressure: p = 75 psi
S = maximum allowable stress: S = 12000 (for aluminum)
E = joint efficiency: E = 1.0
W = total bold load: W = 9000 lb
h_G *= gasket moment arm:* h_G *= 1.66 inch*
L = perimeter of bolted head measured along the centers of bolt holes:
L = 115.5 inch
d = short span of rectangular head: d = 19.25 inch
D = long span of rectangular head: D = 38.50 inch

$$Z = 3.4 - \frac{2.4d}{D} = 3.4 - \frac{(2.4)(19.25)}{38.50} = 2.20$$

$$t = (19.25)\sqrt{\frac{(2.20)(0.3)(75)}{(12000)(1.0)} + \frac{(6)(9000)(1.66)}{(12000)(1.0)(115.5)(19.25)^2}} = 1.26 \text{ inch}$$

Conclusion: To provide a factor of safety, we will use $t = 2.0$ inch for the thickness.

Using a wall thickness of t = 2.0 inch (t = 1.5 inch), we obtain for the maximum allowable working pressure: p_{MAWP} = 193 psi (p_{MAWP} = 107 psi).

(D) **Helium Jacketing (cylinder with elliptical heads):**

Since the dimensions of the outer shell of the helium jacket are almost the same as those of the vacuum vessel, the results of the design calculations are essentially identical to those for the vacuum vessel. Thus no calculations have been performed.

- **testing**

Thermal Shock Test on Ti LH2 Vessel

March 21, 2003

TESTING: Titanium Liquid Hydrogen Vessel

PURPOSE: To determine if this vessel will develop leaks when experiencing extreme temperature fluctuations.

On this date, this vessel was evacuated to $6x10^{-6}$ torr and dunked into liquid nitrogen. Within the liquid nitrogen, vacuum levels shifted to $5.4x10^{-6}$ torr. Upon reaching thermal equilibrium with nitrogen, the vessel was quickly lifted out of the nitrogen, helium leak-checked, and then dunked back in. After four such cycles, the vessel was allowed to warm to room temperature, and helium leak-checked again.Throughout testing, helium leak rates never rose above the base leak rate of $1.0x10^{-9}$ cc/s.

Test Performed By:
Vivek Jeevan
Bill Lozowski
John Vanderwerp

Approved By:
Bill Lozowski

- **finite element analysis**

The results of the finite element analysis on the LH_2 vessel as performed by the ARES Corporation are included in the Appendix .These recommendations from the FEA analysis for the shape of the vessel were incorporated directly into the design of the Al and Ti vessels. The design pressures were later confirmed by pressure tests.

- **material data sheets (M. Snow, H. Nann)**

Copies of the relevant material data sheets are in the Appendix. All of the materials listed above are ASME Code approved materials for use with liquid hydrogen as specified in the NASA safety references [1,2]. The NASA safety standards are in accordance with the ASME Code [9,10].

- **welding certificates**

- **vacuum checking (M. Snow)**

The LH_2 target vessel, main vacuum, helium jacket, and all associated joints will be helium leak tight at all temperatures encountered on the 10E-9 bar-cc/sec level. The radiation shields are not vacuum enclosures and will include reentrant vent holes to allow efficient pump-down of the main vacuum.

- **design pressures (H. Nann, 8-22-01)**

Table 2 lists the vessels which will be pressure tested, the operating, working, and design pressures, the maximum internal pressures, and the proposed settings for rupture disks and pressure relief valves. All components will be tested to their design pressures. Recall that atmospheric pressure at LANL is 11.2 psia.

Table 2: *Important Pressures Associated with the Hydrogen, Helium, and Vacuum vessels*

Object					
	Normal Operating Pressure	Calculated Maximum Pressures (from ASME CODE)	Internal Maximum Allowable Working Pressure (from ASME CODE)	Pressure Relief Valve Setpoint	Rupture Disk Setpoint
LH2 target vessel	15 psia	Internal: 156 psia External: 44 psia	70 psig (81 psia at LANL)	30 psig (41 psia at LANL)	50 psig (61 psia at LANL)
Main Vacuum Vessel	vacuum	Internal: 141 psia External: 29 psia	70 psig (81 psia at LANL)	5 psig (16 psia at LANL)	30 psig (41 psia at LANL)
Helium Jacketing	18 psia (14 psia at Los Alamos)	Internal: 141 psia External: 29 psia	70 psig (81 psia at LANL)	30 psig (41 psia at LANL)	50 psig (61 psia at LANL)

Design Pressures, Operating Pressures, Maximum Allowed Working Pressures

1. LH_2 Flask (cylinder with elliptical heads):
Material: 6061-T6 aluminum except for AZ31C-H24 magnesium alloy entrance window; wall thickness of cylindrical shell 0.10 inch, wall thickness of Mg entrance window 0.125 inch, and wall thickness of Al exit window 0.15 inch.
(A) Design pressure (calculated according to CODE formulae): internal: 159 psia (10.8 atm) - external: 44 psia (3.0 atm)
(B) Normal operating pressure: 10.2 psia (0.7 atm); the atmospheric pressure at Los Alamos is 11.2 psia.
(C) Maximum allowable working pressure (internal): 70 psig (4.8 atm)
(D) Relief paths: single 1.5-inch I.D. piping up to pressure relief valve and rupture disk
(E) Relief valve flow capacity: 0.20 lb/s
(F) Pressure relief valve set point: 7 psig
(G) Rupture disk set point: 75 psig

2. Insulating Vacuum Vessel (cylinder with elliptical heads):
Material: 6061-T6 aluminum except for unalloyed titanium entrance window; wall thickness 0.12 inch
A) Design pressure (calculated according to CODE formulae): internal 83 psia (5.6 atm) - external: 29 psia (2.0

atm)

B) Normal operating pressure: vacuum

C) Maximum allowable working pressure (internal): 70 psig (4.8 atm)

D) Relief paths: single 2.5-inch I.D. piping up to pressure relief valve and rupture disk

E) Relief valve flow capacity: 0.50 lb/s

F) Pressure relief valve set point: 20 psig

G) Rupture disk set point: 75 psig

3. Helium Jacketing:

Material: 6061-T6 aluminum except for unalloyed titanium entrance window; wall thickness 0.12 inch

A) Design pressure (calculated according to CODE formulae): internal 83 psia (5.6 atm) - external: 29 psia (2.0 atm)

B) Normal operating pressure: 18 psia (1.2 atm); at Los Alamos 13.5 psia.

C) Maximum allowable working pressure (internal): 70 psig (4.8 atm)

D) Relief paths: single 0.75-inch I.D. piping up to pressure relief valve and rupture disk

E) Relief valve flow capacity: 0.05 lb/s

F) Pressure relief valve set point: 20 psig

G) Rupture disk set point: 75 psig

- **low temperature seals (M. Snow, 2-22-01, modified 8-18-02 by WMS)**

There will be two Conflat flanges on the target flask. Such seals are known to be reliable at cryogenic temperatures. Our thermal cycling tests confirm their low-temperature reliability of these seals for all possible flange and metal o-ring combinations which are possible given the relative hardness of the materials in different combinations.

Cold Cycling Results

PROCEDURE

Three basic steps are taken to test each joint:

1.) Cool (and leak check)

2.) Heat (and leak check)

3.) Repeat

Cooling

The jointis dunked into liquid nitrogen. Joint temperature drops from room temperature to the temperature of liquid nitrogen, 77K, , in roughly 4 minutes[1]. Equilibrium is visually observed when all major bubbling has ceased.

Leak checking

Leak checking is performed with an Inficon UL 200.

Slightly different leak detector background levels are reached each time a joint is tested. This level reached is called the *base leak rate*, and becomes the vacuum standard for that test.

Heating

After being cooled, the joint is heated back to room temperature in roughly 4 _ minutes[2], by means of a heat gun. A digital pyrometer measures the temperature of the joint. In some tests, different metals at the joint reach slightly different temperatures, and the listed joint temperature is the average of the two metals. Each joint is heated up to ~70ºC at least once during testing.

Repeat

Each joint is thermally cycled around 6 times

RESULTS OF LEAK TESTS

All tests and steps are listed in chronological order. A brand new gasket was used for each test. All other materials were reused. Bronze split lock washers were bent into proper shape prior to each test.

JOINT TYPE	**Step taken**	**Result of leak check**
		base leak rate 7×10^{-10} cc/s
1.33" CF Ti mini-flange	cooled	No leak
connected to	heated	No leak
1.33" CF SS mini-flange	cooled	No leak
	heated	No leak
gasket: copper	cooled	No leak
6 bolts: 8-32 × 7/8 socket cap	heated	No leak
	cooled	No leak

[1] this value taken as an average over 15 trials. Time will vary depending on metals, and initial temps
[2] this value taken as an average over 11 trials. Time will vary depending on metals, and temp heated to

6 nuts: SS hex	heated	No leak
6 washers: SS split lock	cooled plastic bag	No leak
	saturation test[3]	

<u>JOINT TYPE</u>	**Step taken**	**Result of leak check** base leak rate 6×10^{-10} cc/s
1.33" CF SS mini-flange	cooled	no leak
connected to	1.33" flanges heated to 50ºC	no leak
1.33" CF SS mini-flange	2.75" flanges heated to 50ºC	
	cooled	no leak
gasket: copper	1.33" flanges heated to 35ºC	no leak
6 bolts: _-20 × 1.5" hex head	2.75" flanges heated to 30ºC	
6 nuts: SS	cooled	no leak
6 washers: SS split lock	1.33" flanges heated to 38ºC	no leak
	2.75" flanges heated to 35ºC	
ALSO	cooled	no leak
	1.33" flanges heated to 70ºC	no leak
2.75" CF SS Vent Stub	2.75" flanges heated to 55ºC	
connected to		
2.75" CF Ti Vent Stub		
gasket: aluminum		
6 bolts: _-20 × 1.5" hex head		
6 nuts: SS		
6 washers: SS split lock		

[3] a plastic bag is filled with helium and tied around cooled joint. this is simply a more aggressive leak test

<u>JOINT TYPE</u>	**Step taken**	**Result of leak check**
		base leak rate 7.5×10^{-10} cc/s
2.75" CF SS Vent Stub	initial leak test	no leak
connected to	cooled	no leak
2.75" CF Ti Vent Stub	heated to 45ºC	no leak
	cooled	no leak
gasket: aluminum (brand new)	heated to 35ºC	no leak
6 bolts: _-20 × 1.5" hex head	cooled	no leak
6 nuts: SS	heated to 40ºC	no leak
6 washers: bronze split lock	cooled	no leak
	heated to 30ºC	no leak
	cooled	no leak
	heated to 35ºC	no leak
	cooled	no leak
	heated to 35ºC	no leak
	cooled	no leak
	heated to 48ºC	no leak
	cooled	no leak
	heated to 68ºC	no leak

<u>JOINT TYPE</u>	**Step taken**	**Result of leak check**
		base leak rate 3.5×10^{-10} cc/s
2.75" CF SS Vent Stub	initial leak test	no leak
connected to	cooled	no leak
2.75" CF Ti Vent Stub	heated to 32ºC	no leak
	cooled	no leak
gasket: copper	heated to 33ºC	no leak
	cooled	no leak

6 bolts: _-20 × 1.5” hex head	heated to 40ºC	no leak
6 nuts: SS	cooled	no leak
6 washers: bronze split lock	heated to 40ºC	no leak
	cooled	no leak
	heated to 37ºC	no leak
	cooled	no leak
	heated to 78ºC	no leak

<u>JOINT TYPE</u>	**Step taken**	**Result of leak check**
		base leak rate 3×10^{-10} cc/s
2.75” CF SS Vent Stub	initial leak test	no leak
connected to	cooled	no leak
2.75” CF gold-plated	heated to 31ºC	no leak
aluminum Vent Stub	cooled	no leak
	heated to 38ºC	no leak
gasket: aluminum	cooled	no leak
6 bolts: _-20 × 1.5” hex head	cooled	no leak
6 nuts: SS	heated to 40ºC	no leak
6 washers: bronze split lock	cooled	no leak
	heated to 32ºC	no leak
	cooled	no leak
	heated to 28ºC	no leak
	cooled	no leak
	heated to 80ºC	no leak

JOINT TYPE	**Step taken**	**Result of leak check** base leak rate 1.0×10^{-10} cc/s
2.75" CF SS Vent Stub	initial leak test	no leak
connected to	cooled	no leak
2.75" CF Ti Vent Stub	heated to 27ºC	no leak
	cooled	no leak
gasket: copper	heated to 46ºC	no leak
6 bolts: _-28 × 1.5", 316 SS	cooled	no leak
socket head	heated to 41ºC	no leak
6 nuts: _-28 SS hex	cooled	no leak
6 washers: bronze split lock	heated to 34ºC	no leak
	cooled	no leak
	heated to 35ºC	no leak
	cooled	no leak
	heated to 72ºC	no leak

JOINT TYPE	**Step taken**	**Result of leak check** base leak rate 1.2×10^{-10} cc/s
2.75" CF SS Vent Stub	initial leak test	no leak
connected to	cooled	no leak
2.75" CF Ti Vent Stub	heated to 35ºC	no leak
	cooled	no leak
gasket: aluminum	heated to 39ºC	no leak
6 bolts: _-28 × 1.5", 316 SS	cooled	no leak
socket head	heated to 43ºC	no leak
6 nuts: _-28 SS hex	cooled	no leak
6 washers: bronze split lock	heated to 35ºC	no leak
	cooled	no leak

	heated to 39ºC	no leak
	cooled	no leak
	heated to 85ºC	no leak

JOINT TYPE	**Step taken**	**Result of leak check** base leak rate 2.0×10^{-10} cc/s
2.75" CF SS Vent Stub	initial leak test	no leak
connected to	cooled	no leak
2.75" CF Ti Vent Stub	heated to 38ºC	no leak
	cooled	no leak
gasket: copper	heated to 30ºC	no leak
6 bolts: _-28 × 1.25" SS	cooled	no leak
MDC 12 pt. head	heated to 45ºC	no leak
6 nuts: _-28 SS hex	cooled	no leak
no washers	heated to 44ºC	no leak
	cooled	no leak
	heated to 36ºC	no leak
	cooled	no leak
	heated to 78ºC	no leak

JOINT TYPE	**Step taken**	**Result of leak check** base leak rate 2.0×10^{-10} cc/s
2.75" CF SS Vent Stub	initial leak test	no leak
connected to	cooled	no leak
2.75" CF Ti Vent Stub	heated to 36ºC	no leak
	cooled	no leak
gasket: aluminum	heated to 43ºC	no leak

6 bolts: _-28 × 1.25” SS	cooled	no leak
MDC 12 pt. head	heated to 30ºC	no leak
6 nuts: _-28 SS hex	cooled	no leak
no washers	heated to 33ºC	no leak
	cooled	no leak
	heated to 32ºC	no leak
	cooled	no leak
	heated to 78ºC	no leak

JOINT TYPE	**Step taken**	**Result of leak check**
		base leak rate 9×10^{-10} cc/s
2.75” CF SS Vent Stub	initial leak test	no leak
connected to	cooled	no leak
2.75” CF gold-plated	heated to 29ºC	no leak
aluminum Vent Stub	cooled	no leak
	heated to 29ºC	no leak
gasket: aluminum	cooled	no leak
6 bolts: _-20 × 1.5” brass	heated to 30ºC	no leak
hex head	cooled	no leak
6 nuts: _-20 brass hex	heated to 42ºC	no leak
6 washers: bronze split lock	cooled	no leak
	heated to 36ºC	no leak
	cooled	no leak
	heated to 86ºC	no leak

<u>JOINT TYPE</u>	**Step taken**	**Result of leak check**
		base leak rate 1×10^{-9} cc/s
2.75" CF SS Vent Stub	initial leak test	no leak
connected to	cooled	no leak
2.75" CF Ti Vent Stub	heated to 27ºC	no leak
	cooled	no leak
gasket: copper	heated to 40ºC	no leak
6 bolts: _-20 × 1.5" brass	cooled	no leak
hex head	heated to 29ºC	no leak
6 nuts: _-20 brass hex	cooled	no leak
6 washers: bronze split lock	heated to 28ºC	no leak
	cooled	no leak
	heated to 37ºC	no leak
	cooled	no leak
	heated to 78ºC	no leak

<u>JOINT TYPE</u>	**Step taken**	**Result of leak check**
		base leak rate 6×10^{-10} cc/s
2.75" CF SS Vent Stub	initial leak test	no leak
connected to	cooled	no leak
2.75" CF Ti Vent Stub	heated to 25ºC	no leak
	cooled	no leak
gasket: aluminum	heated to 29ºC	no leak
6 bolts: _-20 × 1.5" brass	cooled	no leak
hex head	heated to 43ºC	no leak
6 nuts: _-20 brass hex	cooled	no leak
6 washers: bronze split lock	heated to 32ºC	no leak
	cooled	no leak

	heated to 40ºC	no leak
	cooled	no leak
	heated to 72ºC	no leak

JOINT TYPE	**Step taken**	**Result of leak check**
		base leak rate 1×10^{-6} cc/s
VCR Seals	initial leak test	no leaks
	cooled	no leaks
1 Nickel	heated to 20ºC	no leaks
1 Copper	cooled	no leaks
1 Stainless Steel	heated to 20ºC	no leaks
	cooled	no leaks
	heated to 29ºC	no leaks
	cooled	no leaks
	heated to 39ºC	no leaks
	cooled	no leaks
	heated to 35ºC	no leaks
	cooled	no leaks
	heated to 98ºC	no leaks

Relief System and Vent Line

- **specifications (H. Nann, 6-20-01)**

Table 3 contains a list of the various parts of the relief system along with their performance requirements. Each component from the individual enclosures possesses a primary relief system consisting of a spring-loaded pressure relief valve and a secondary relief system consisting of rupture disk in parallel with the relief valve. All pressure reliefs are connected to a large (6” diameter) vent line which is filled with nitrogen gas at atmospheric pressure and conducts the gas to the outside of the experimental hall. Fig. 4 shows the diagram of the relief and vent system.

Table 3: *Specifications of Vent Lines and the Main Exhaust Line*

Vent Lines	Mechanical and Conductance Properties of Vent Lines/Blowoffs			Pressure in Worst-Case Failure
	Dimensions	Material	Mass Flow Capacity	
LH_2 target vent line	1.5 “diameter resistance coefficient K = 10	304 stainless steel	0.20 lb/sec	47 psia
Main Vacuum vent line	2.5” diameter resistance coefficient K = 10	304 stainless steel	0.50 lb/sec	43 psia
Main exhaust line	6” diameter	304 stainless steel		

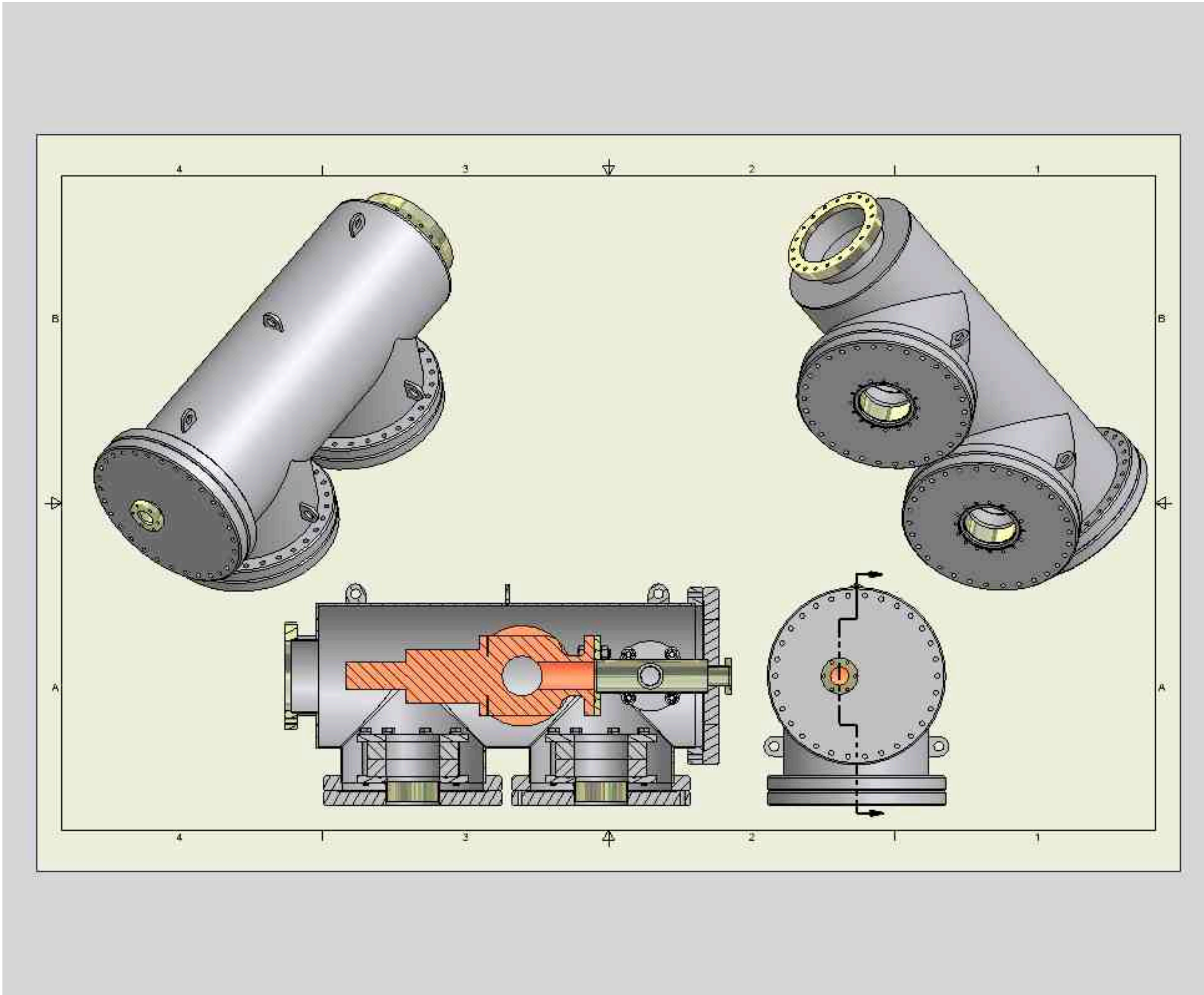


Figure XXX: rendered drawing of the connection between the vent lines to the relief valves and burst disks and the vent stack. The basic idea is to enclose the burst disks and relief valves in the same helium atmosphere as will be present in the vent stack.

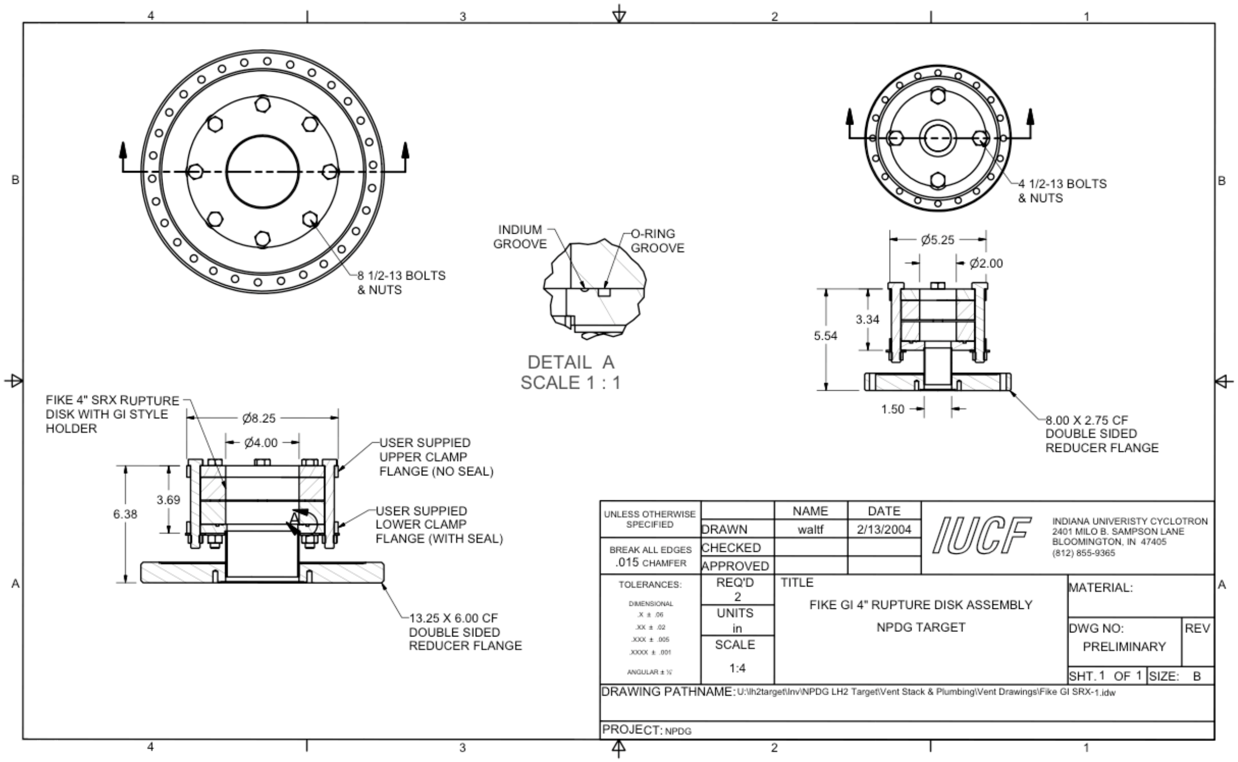


Figure XXX: design for the seals for the burst disks. The design incorporates an indium groove inside of the o-ring groove so that there is no diffusion of helium gas from the vent stack into the main vacuum system. This design produces no mechanical modification to the burst disks themselves, whose quality assurance procedures are therefore identical to those for standard components.

- **relief valve specifications (J. Novak, 11-10-01, modified by H. Nann, 9-10-02)**

The LH_2 target system consists of three components: a target flask containing the liquid hydrogen, an insulating vacuum vessel, and a helium jacket surrounding the vacuum vessel. All components were designed according to the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 and 2 [9]; ASME B31.3 Code for Pressure Piping – Process Piping [10]; CGA S-1.3 Pressure Relief Device Standards – Part 3 – Stationary Storage Containers for Compressed Gases [6] (referred to as CODE). Each component is equipped with a primary relief system of a spring-loaded pressure relief valve and a parallel, secondary relief system consisting of a rupture disc. All pressure reliefs are connected to a large size (6 inch diameter 304L stainless steel pipe) vent line, which is filled with helium at atmospheric pressure, to the outside of the building.

NPDGamma LH2 Target Relief Valve Sizing

LH2 Flask Relief Valve

Assume flow is caused by loss of insulating vacuum.
Max. H2 flowrate = 0.2 lbm/s (per Nann)
Delta-P through 1.5” I.D. vent line to relief valve = 32.5 psid (per Novak, 8/8/01)

Requirements:
- Must be high-vacuum tight, allowing flask to be evacuated and held evacuated, without leakage of contaminants in.
- Essentially no leakage under pressure up to 85% of set pressure
- Pressure rise of 10% above set pressure at full flow rate is fine. 15% is acceptable.
- Pressures:
  - Normal operation = -14.7 to ~6 psig (0 to ~20 psia)
  - System design pressure = 160 psia (per Nann)
  - Maximum working pressure = 70 psig (per Nann)

Considerations regarding Anderson Greenwood valves:
- Pick from direct-acting spring types since pilot-operated types like AG model 91 will open when flask is evacuated (!).
- Pick from AG models 81 (good for cryo temperatures) or 83 (probably gives tighter vacuum seal). Since either valve will survive cryo temperatures without damage, pick the model 83.

Considerations regarding physical size of valve
- Using AG’s “Safety Size” valve selection program, select candidate valve body sizes, orifice sizes, and minimum set pressures that will pass 0.2 lbm/s of H2 gas at 70 F.

Candidate Valves

Set pres. (psig)	Valve model	Orifice designation	Smallest pipe size
20	83	J	2 x 3 FNPT
34	83	H	2 x 3 FNPT

62	81, 83	G	1.5 x 2 FNPT

Set pressures up to 62 psig have the same physical size. A valve with 62 psig set pressure is smaller, but 62 psig seems a bit high, considering the normal operating pressure range of the system. Better to have a larger margin of safety over the design pressure.

Is it better to have the H or the J orifices?
For a given set pressure, spring force increases proportional to nozzle area. But seal load, unless there is a mechanical stop, increases with nozzle radius. Thus larger orifice helps sealing (to first order). Thus, pick the J orifice (1.287 in^2 flow area).

What is a good set pressure?
Pick 30 psig.
It is far from the operating pressure. 30 psig / 6 psig = 5:1
It is far from the design pressure. 160 psia / (30 + 14.7) psia = 3.6:1
The weep point is far from the operating pressure
Weep point = 85% of set point = 22.5 psig (see AG catalog p. 56)
Ratio to operating pressure = 22.5 / 6 psig = 4:1
Flow rate at set pressure: AG Safety Size gives ASME Rated Capacity of 0.306 lbm/s with J orifice.

LH2 Flask Rupture Disk

Fike Co. sells model SR-H rupture disks that have a molded-on gasket and fit Tri-Clover flanges.
The Fike catalog does not give flow resistance, K, for a ruptured SR-H disk, but gives K for the similar HOV disk/flange set = 2.02 and K for the CPV-C disk = 3.5. These numbers indicate a rather free opening after the disk ruptures.
The SR-H is listed as suitable for full vacuum load.

Are they vacuum-tight? Dallas Clayton (Scientific Sales, 505-266-7861) says they are.

Pick 3” size, same as discharge line size of relief valve. We will have to use a 2 to 3 inch diameter adapter somewhere, either before or after the disk, so it may as well be after, giving us the largest flow capacity. Prices of 2” and 3” disks are essentially the same.

Tri-Clover catalog lists the 3” size Model 13MHHM flanges rated at 300 psi.

What is a good set pressure?
Pick 80 psig.
It is adequately far from the relief valve set point.
(Note: 50 psid would work. However, the rupture disk for the vacuum vessel needs to be set at 80 psid. Since 80 psid will work for the LH2 flask, lets use it and have only one item to stock.)
Cheapest disk burst pressure tolerance range = +0 –10% ➔ 80 to 72 psid burst pressure

Maximum pressure ahead of relief valve at full flow = 1.1 x set pressure = 33 psid
Ratio is 33 / 72 = 46%, which is a great margin. The burst disk should not break accidentally.
It is adequately far from the design pressure. (80 + 14.7) / 160 psia = 0.59

Vacuum Vessel Relief Valve and Rupture Disk

Assume flow is caused by total rupture of LH2 flask.
Max. H2 flow rate = 0.5 lbm/s (per Nann)
Delta-P through 2.5” I.D. vent line to relief valve = 28.2 psid (per Novak, 8/24/01)

Requirements:
Must be high-vacuum tight, with leakage rates low enough that vessel can be isolated from pump system for weeks.
Essentially no leakage under pressure up to 85% of set pressure
Pressures:
Normal operation = vacuum
Vacuum vessel design pressure = 150 psia (per Nann)
Maximum working pressure = 70 psig (per Nann)

The controlling requirement is that the relief devices (valve and rupture disk) must protect the weakest components in the vacuum system. These are the vacuum pump and gages. Pressure ratings for such components are not normally given, but are surely in excess of 15 psig. Thus, pick relief devices with low relief pressures, around 15 psi or lower.

None of the AG valves will work. The largest one requires a 60 psi inlet pressure to be able to pass the required mass flow.

A suitable set of devices would be a rupture disk set at a low pressure combined with a spring-loaded relief/vent valve. Neither of the devices should ever open unless there is a catastrophic failure of some component inside the vacuum jacket. The spring-loaded relief valve would not be counted on for Code compliance since no ASME-rated valve is available in a reasonably small size. Instead, any sort of spring-loaded valve could be used to vent any small amounts of gas that may enter the vacuum chamber, thus protecting the rupture disks from unnecessary rupture. The rupture disk would be the primary device used to achieve Code compliance. A second disk could be used if additional redundancy was desired.

Suitable devices would be:
Rupture disk: Fike model SR-H in 3” size with a 15 psi burst pressure (the lowest pressure that Fike offers).
Relief/vent valve: Circle Seal Controls Inc. model 200 check valve, brass body, Buna N o-ring, 2” FNPT ports, 4 psid cracking pressure, part no. 249B-16PP-4.

Helium Vessel Relief Valve and Rupture Disk

Assume flow into helium vessel is due to rupture of H2 pipe(s) inside helium jacket. Pressure / flow in these pipes is assumed to be

coincident with the worst condition to befall the LH2 vessel, namely loss of insulating vacuum or operation of ‘fast empty’ electric heater. Thus, the flow could be the same as the worst flow out of the LH2 vessel, which is = 0.2 lbm/s (per Nann)
Delta-P through 1.5” I.D. vent line to relief valve = 32.5 psid (per Novak, 8/8/01)

Thus, use the same relief valve and rupture disk that are used on the LH2 vessel. They are adequate for the flow, they simplify ordering and piping design, and they provide some measure of redundancy in spare parts.

Note: Selection of this failure scenario implies that the pipe from the helium vessel to the relief devices is at least 1.5 inch I.D.

- **design and dimensional calculations (H. Nann, 8-22-01)**

Calculations based on the Bates Internal Report # 90-02 [21] and the Crane Technical Paper No. 410 [11] were performed to determine the size of the relief plumbing such that the mass flow remains subsonic at all times and that the maximum pressure in each component remains well below its bursting point. Based on the formulae and algorithms in these reports, two computer programs were written. The first program calculates the mass evolution rate and boil-off time from geometric information and the properties of both the target material and vacuum spoiling gas, whereas the second program yields the maximum pressure occurring during the discharge through the pressure relief system. The information that was used as input to the calculation as well as their results are given in tables 4 and 5. The calculation of the maximum pressure in the target flask and the vacuum vessel during the catastrophic discharge takes into consideration all the pipes and bends up to the main exhaust line, including the pressure relief valve. Furthermore, it is assumed that all the mass flows out through the pressure relief system into the main exhaust line to the outside of the ER2 building and not through the fill line relief valves. The friction factor for each relief system was taken from the Crane Technical Paper No. 410. They were f = 0.021 for a 1.5 inch inner diameter smooth pipe and f = 0.019 for a 2.5 inch inner diameter smooth pipe. The resistance coefficients K for the two relief systems were calculated for each component of the relief vent line and then added up. (It should be noted that K is constant for any given obstruction under all conditions of flow.) The results were between K = 8 and K = 10. Thus a value of K = 10 was used for calculating the maximum pressure. For more details see appendix 2.

Table 4: *Boil-off Rates of 21 Liter of Liquid Hydrogen*

	Target Flask		Vacuum Vessel	
Heat Flux into Target [W/m^2]	13,000*	40,000**	100,000	100,000
Surface area [m^2]	0.50	0.25	0.5	1.0
Boil-off Time [s]	102	66	13.2	6.6
Mass Boil-off Rate [lb/s]	0.032	0.049	0.25	0.49

* *Calculated under the assumption that the target flask is surrounded by air.*
** *10kW of (electrical) power transferred to lateral surface of target flask.*

The final results show that, in the case of a catastrophic vacuum failure to air, the target flask is subjected to a pressure of no more than 47 psia if the inner diameter of the pressure relief piping is 1.5 inch, if a boiloff rate of 0.20 lb/s is assumed. The maximum pressure in the vacuum vessel for the case of a rupture of the target flask is 43 psia for an inner diameter of the pressure relief piping is 2.5 inch, , if a boiloff rate of 0.50 lb/s is assumed. Both pressures are well below the 100 psia pressures that the target flask and vacuum vessel will be tested at. Since the pressure relief system for the vacuum vessel can respond safely to a possible catastrophic rupture of the target flask, the pressure relief system of the helium jacket does not need to handle a large mass flow rate in the unlikely event of a leak in the wall between the vacuum vessel and the helium jacket. Thus a pressure relief system with an inner diameter of 0.75-inch piping is considered adequate.

Table 5: *Response of the pressure relief system for various mass flow rates and tubing sizes. A value of K = 10 was assumed.*

	Target Flask					Vacuum Vessel	
Mass Flow Rate [lb/s]	0.05	0.10	0.05	0.10	0.20	0.50*	0.50*
I.D. of Relief Pipe [in]	1.0	1.0	1.5	1.5	1.5	2.0	2.5
Sonic Mass Flow Rate [lb/s]	0.13	0.13	0.29	0.29	0.29	0.52	0.81
Maximum Pressure [psia]	28.4	52.5	18.0	26.0	47.0	65.2	42.6

* *Mass flow rate when all of the 21 liter of LH_2 is at once in contact with the vacuum vessel wall at 293 K.*

In summary, pressure relief systems with a 1.5-inch inner diameter discharge pipe for the target flask and a 2.5-inch inner diameter discharge pipe for the vacuum vessel will respond safely to catastrophic failures. Furthermore, the safety relief piping for the helium jacket will have an inner diameter of 0.75 inch.

- **main exhaust line (H.Nann, 06-04-03)**

The pressure relief vent lines from the LH_2 target flask and the surrounding insulating vacuum vessel are connected to a 6 inch inner diameter main exhaust line which, in case of an accident or emergency, conducts the hydrogen gas to the outside (above the roof) of the ER2 building. This main exhaust line has to handle the flow from all discharges and thus has a capacity, which is sufficient to avoid over-pressurizing the weakest part of the system. A check valve is provided in the exhaust line near the atmospheric discharge to limit backflow of air. The exhaust piping is being purged with nitrogen or helium gas to ensure that a flammable mixture will not develop when hydrogen

is introduced.
Since hydrogen gas may be ignited by static electrical charges as it leaves the exhaust piping, a helium gas purge is made available to extinguish any flame. The exhaust stack outside the roof of the ER2 building is suitably located to prevent any fire hazard.
The horizontal portion of the exhaust line from the top of the experimental cave to the wall of the ER2 building has a slight upward grade of x° so that the buoyancy of the hydrogen gas will cause it to flow naturally to the rooftop.
Calculations based on the Bates Internal Report #90-02 [21] and the Crane Technical Paper No. 410 [11] show that the 6-inch inner diameter exhaust line can safely handle a mass flow rate of 2.0 lb/s (four times the assumed boil-off rate of 0.5 lb/s from a catastrophic rupture of the target flask spilling 21 liters of LH_2 into the vacuum vessel) with a pressure build-up of no more than 29 psia. For the total resistance coefficient a value of K = 8 was used. Calculations based on the "K" Factor Tables on p. A-26 to A-229 of Ref 11, assuming a pipe length of 100 feet, two 90 degree elbows and a check valve, give K = 6.9.

- **data sheet**
- **test procedures and results (H. Nann, 8-22-01, modified 5-1-03 WMS)**

(1)

- **Accident Scenario Tests: (May 2003)**

The following tests of the overpressure behavior were performed.

(2) Test of the LH_2 target vessel (similar tests have been performed at JLAB with their cryomodules [16].)

The target vessel, surrounded by one layer of copper heat shielding, was mounted inside the insulating vacuum vessel. Both the target vessel and the heat shield were thermally connected to the top (Cryomech) refrigerator. The exhaust line from the target vessel to the pressure relief valve had an inner diameter of 0.5 inch, was about 50 inches long, and contained three 90-degree elbows. The pressure relief valve was set at 2.4 bar absolute. Pressure and temperature sensors were placed throughout the target and insulating vacuum system.

The target vessel was filled with 18 liter of LN_2. Dry argon was then bled into the vacuum vessel and a constant value of 1 atmosphere was held till all of the LN2 in the target vessel was evaporated. Both the top and bottom refrigerators were operating during the test.

When the pressure in the target vessel exhaust line reached the preset 2.4 bar absolute, the pressure relief valve opened, and the pressure dropped to 2.2 bar, stayed there for 28 minutes, and then dropped slowly to 1 bar. The target was empty after 55 minutes.

The mass of 18 liters of LN_2 is 14.53 kg; it evaporated in Δt = 55 min = 3300 s. Thus the mass flow rate is

$$w_N = \frac{m}{\Delta t} = \frac{14.53kg}{3300s} = 0.0044kg/s = 0.01lb/s$$

Now convert this mass flow rate for nitrogen to the mass flow rate for hydrogen by assuming that the heat flux into the target is the same.

$$w_H = \frac{h_V(N_2)}{h_V(H_2)} w_N = \frac{198.8J/g}{445J/g} \cdot 0.01lb/s = 0.0045lb/s$$

where $h_V(N_2)$ and $h_V(H_2)$ are the enthalpies of vaporization per unit mass for nitrogen and hydrogen, respectively.

This mass flow rate can safely be handled by the designed pressure relief system, which is able to discharge 0.2 lb/s with a maximum pressure build-up of no more than 47 psia.

1. Test of the vacuum vessel:

A foam container with 3 liters of LN_2 was emptied by remote control into the vacuum vessel at room temperature and atmospheric pressure. The target vessel and heat shield were inside the vacuum vessel. Thus the volume, into which the LN_2 expanded, closely modeled that of the operating LH_2 target. The exhaust line from the vacuum vessel to the pressure relief rupture disk had an inner diameter of 0.75 inch. The rupture disk was punctured at 2.3-bar absolute pressure. It took 62 seconds for these 3 liter of LN_2 to evaporate.

The mass of 3 liter of LN2 is 2.43 kg; it evaporated in Δt = 62 s. Thus the mass flow rate through the pressure relief system was

$$w_N = \frac{m}{\Delta t} = \frac{2.43kg}{62s} = 0.04kg/s = 0.09lb/s$$

This corresponds to a mass flow rate for hydrogen of $w_H = 0.04\ lb/s$. Assuming that 21 liter of LH_2 evaporate in the same time – (this assumption can be justified since all of the 21 liters of LH_2 are in contact with the vacuum vessel wall at the same time.) – the mass flow rate is $w_H = 0.28\ lb/s$. Again this mass flow rate can safely be handled by the designed pressure relief system, which is able to discharge 0.5 lb/s with a maximum pressure build-up of no more than 43 psia.

Testing Relief Valves

PURPOSE: It has been found that our relief valves do not entirely close a line below its set cracking pressure. Instead, there may be a range of pressures through which the valves leak. It is therefore important to characterize the leaking of the relief valves.

SETUP: Gaseous helium (or nitrogen) is fed to the relief valve at certain pressures. A hose is attached between the output of the relief valve, and a beaker full of water. As gas leaks through the relief valve, it travels through the hose, and displaces the water in the beaker (in the form of bubbles). Timing the displacement of water in the beaker gives the leak rate, in volume per time, of gas through the relief valve.

RESULTS: RV103 showed no leaks at pressures below its set cracking pressure, as the following data shows:

RV103 (cracks at 200psig)

Pressure [psig]	Flow Rate[mL/s]
190	0
200	unmeasurably fast

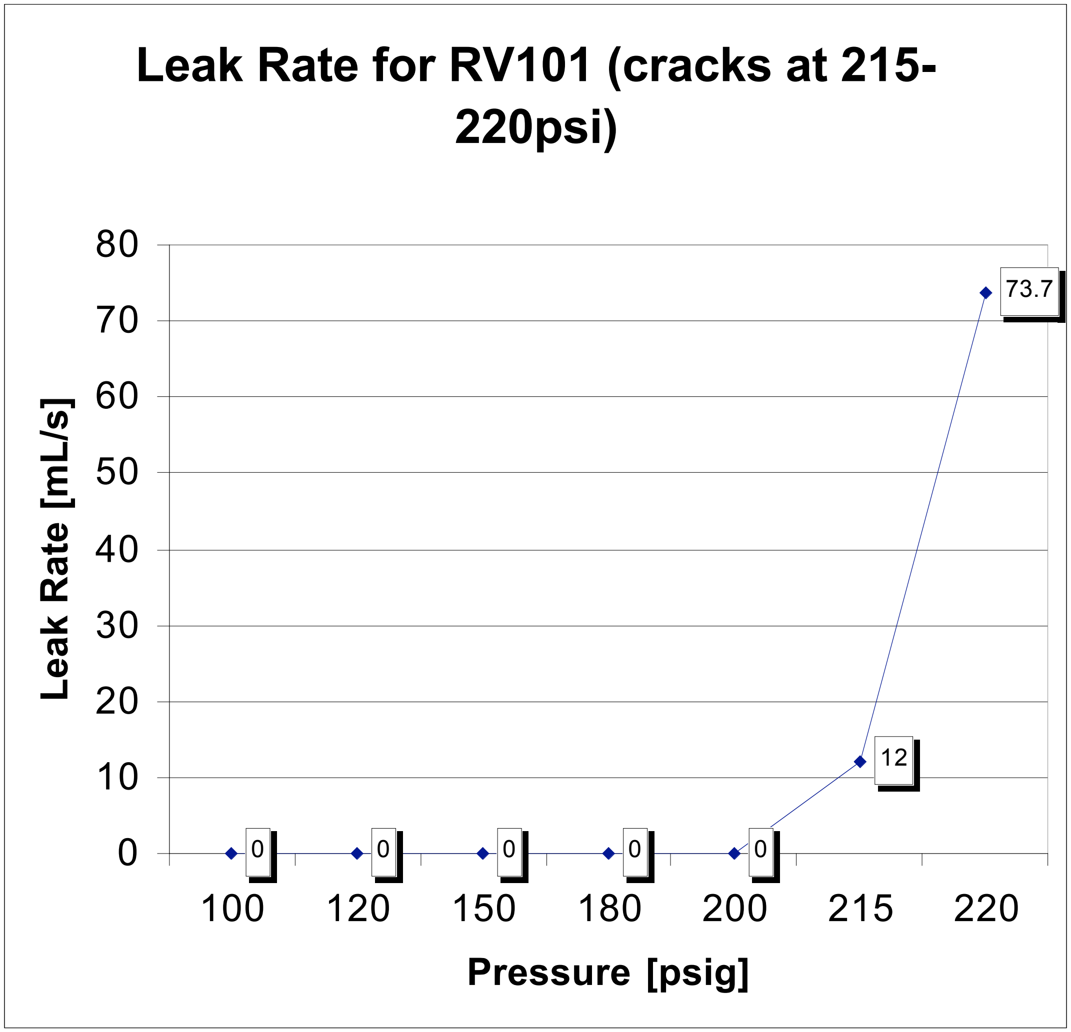
RV104 did not demonstrate a set cracking pressure, but rather a range of 5psig over which is cracked:

RV104 (cracks at 30-35 psig)

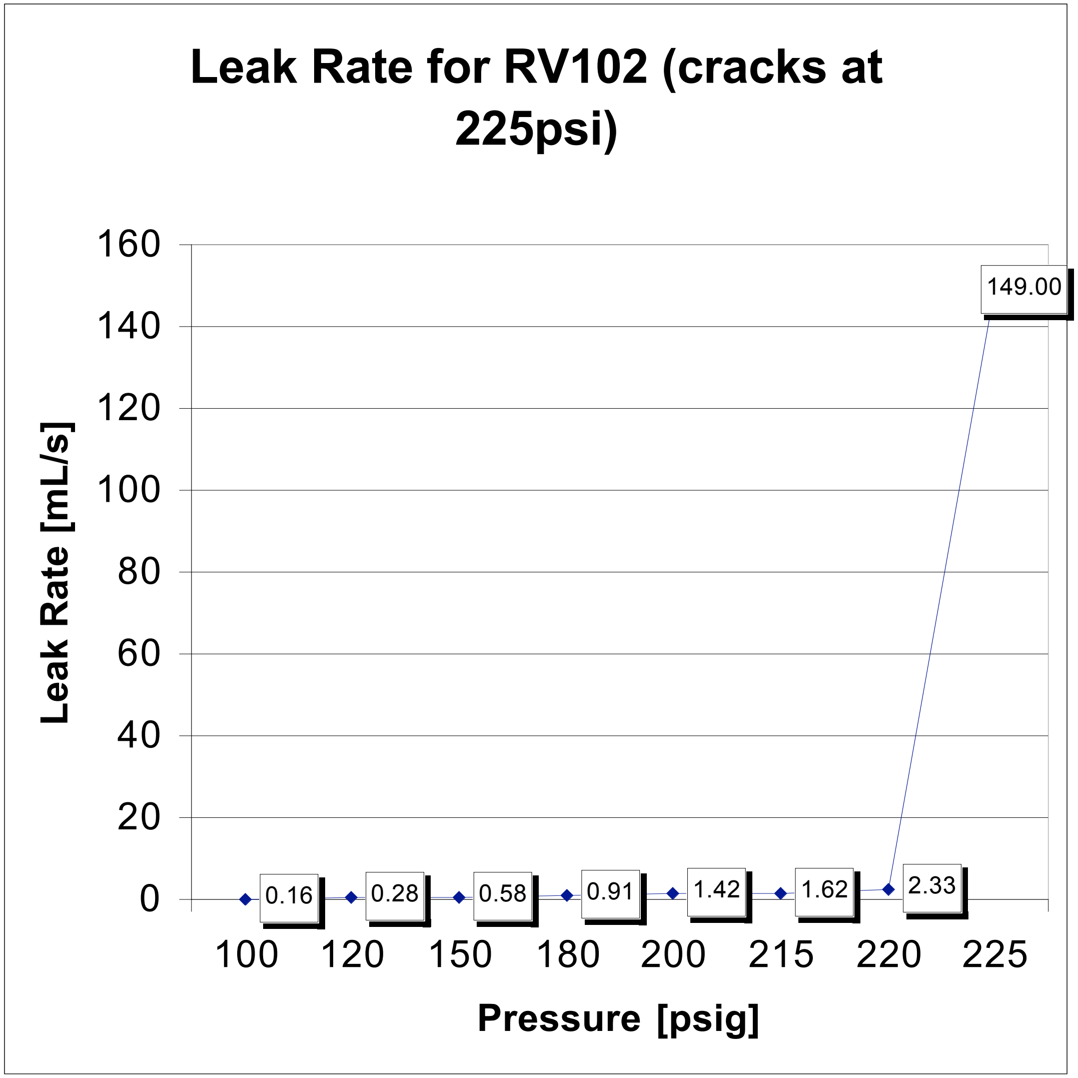
Pressure [psig]	Flow Rate[mL/s]
10	0
20	0
30	12.9

35	unmeasurably fast

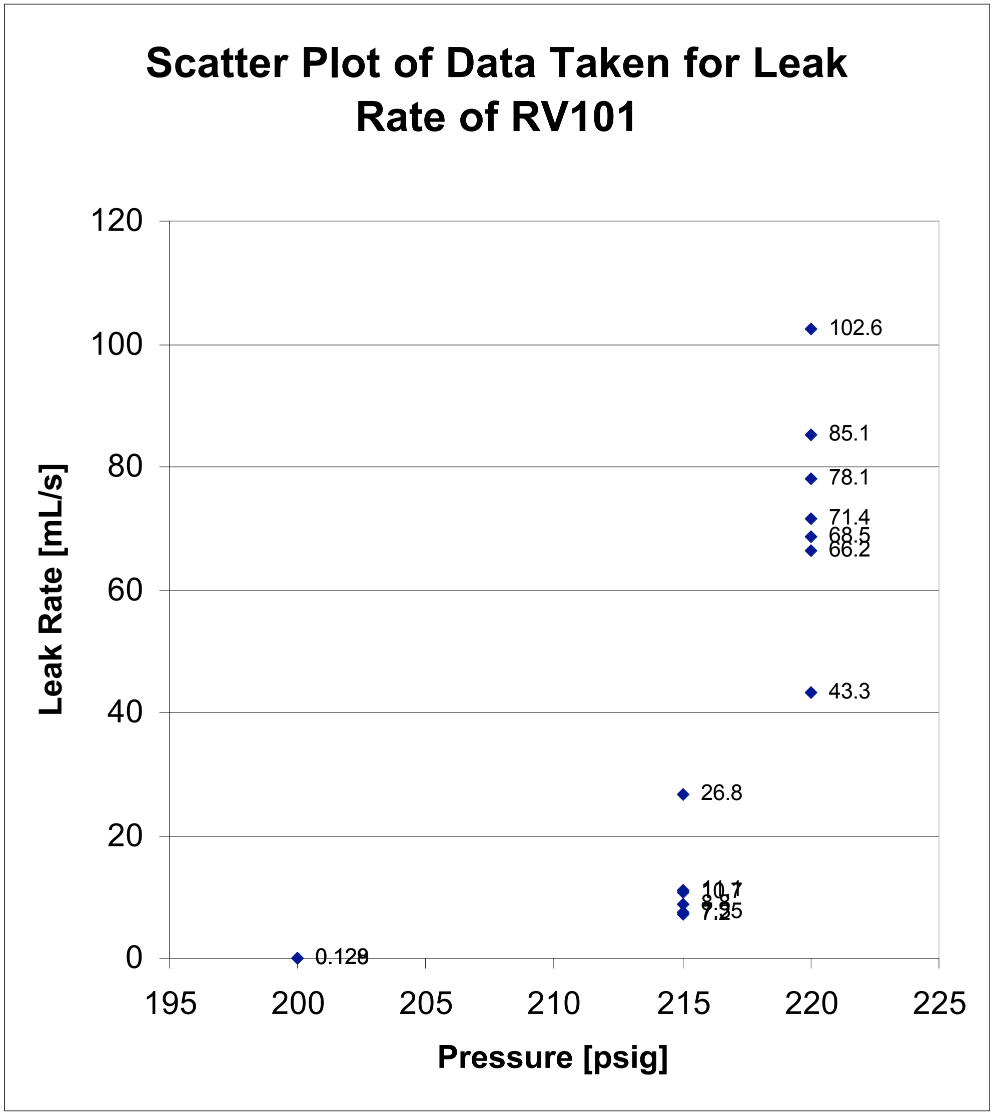
RV101 also showed a range over 5psig over which it cracked:



RV102 showed leaks through a wide range of pressures, yet maintains a distinctive cracking pressure.:



ERRORS: Leak rates at a given pressure, for a given valve, were not very reproduceable. Points plotted above are averages over the data taken. To see the spread of measured leak rates for RV101, a scatter plot is most appropriate:



Here is the raw data for the measured leak rates for RV101,

Raw Relief Valve Data

RV101

Pressure [psig]	Time[s]	Displaced Volume[mL]	Flow Rate[mL/s]
100*	-	-	no leak
120*	-	-	no leak
150*	-	-	no leak
180*	-	-	no leak
200*	15.52	2	0.129
200*	15.66	2	0.128
215	7.46	200	26.8
215	18.07	200	11.1
215	18.74	200	10.7
215	22.72	200	8.80
215	27.20	200	7.35
215	27.78	200	7.20
220	1.95	200	102.6
220	2.35	200	85.1
220	2.56	200	78.1
220	2.80	200	71.4
220	2.92	200	68.5
220	3.02	200	66.2
220	4.62	200	43.3

RV102

Pressure [psig]	Time[s]	Displaced Volume[mL]	Flow Rate[mL/s]
100	10.27	2	.195
100	12.35	2	.162
100	14.67	2	.136
120*	6.16	2	.325
120*	8.24	2	.243
150*	166.62	100	.600
151	180.97	100	.553
180*	94.30	100	1.06
180	131.93	100	.758
200*	58.06	100	1.72
200	90.20	100	1.11
215	61.76	100	1.62
220	41.76	100	2.39
220	43.96	100	2.27
225	1.08	200	185
225	1.77	200	113

RV103

Pressure [psig]	Time[s]	Displaced Volume[mL]	Flow Rate[mL/s]
190*		negligible	negligible flow rate

RV104

Pressure [psig]	Time[s]	Displaced Volume[mL]	Flow Rate[mL/s]
10*	-	-	no leak

200*	?	200	unmeasurably fast

20*	-	-	no leak
30*	8.30	100	12.0
30*	14.55	200	13.7
35*	?	200	unmeasurably fast

* pressure due to Helium gas (otherwise, pressure due to Nitrogen)
Error in pressure is +/- 2psig
Error in volume is +/- 10%

Pressure Test on 24” Bellows

February 18, 2003

PURPOSE: To determine if this bellows can be safely pressurized to 30 psig.

BELLOWS: 24” long
position in gas handling system: foreline of TP201

On this date, this bellows was pressurized to 30 psig. At maximum pressure, it expanded to 28” long (flange-to-flange). After repeated exposures to 30 psig, a hydrogen leak test confirmed (to a leak rate of 1×10^{-9} cc/s) that the bellows did not crack.

Test Performed By: Approved By:
Vivek Jeevan Bill Lozowski

Pressure Test on Hydrogen Target Isolation Valve

February 17, 2003

PURPOSE: To determine if this valve’s bellows can be safely pressurized to 80psig, which is 1.1 times the maximum working pressure of the system.

VALVE: MDC Vacuum Products Corporation
model #: AV—150M
serial #: 94-47248
position in gas handling system: V128
note: contains copper gasket seat under the bonnet to seal the bellows

On this date, this valve was pressurized to 80pisg. While pressurized, it was repeatedly opened and closed, thereby expanding and contracting its bellows. After repeated exposures to 80psig, a hydrogen leak test confirmed (to a leak rate of 2×10^{-9} cc/s) that the bellows did not crack.

Test Performed By: Approved By:
Vivek Jeevan Bill Lozowski

Summary of testing documentation for the NPDG LH2 target

M. Snow, 5-1-03

This is a brief summary of the tests performed by vendors who have fabricated parts of the NPDG LH2 target organized by item and vendor. All welding for all parts was performed by certified welders.

(1) Main vacuum chamber and windows

Ability Engineering Technology
16140 Vincennes Ave.
South Holland, IL 60473
Michael Morgan, president
(708)-331-0025
fax (708)-331-5090

The main vacuum chamber is an aluminum vessel with internal channels which expose all weld joints and o-ring seals to helium gas from the outside. In addition there are two sets of double windows at the entrance and exit for the neutron beam. The tests discussed here were performed with magnesium windows.

Materials certification

The 6061-T651 aluminum stock (from which the entire box part of the vessel was machined from a single piece to reduce weld joints) is from A. M. Castle Co, 3400 N. Wolf Rd., Franklin Park, IL 60131, 1-800-367-2586 amd made by Kaiser Aluminum. Test results for the lot: tensile strength 50,000 PSI, yield strength 46300 PSI, elongation 15.9%

The 6061-T651 aluminum for the end plate is from Empire Resources, One Parker Plaza, Ft. Lee, NJ 07024 made by Hulett

Aluminum Rolled products Ltd. Test results: tensile strength 46,255 PSI, yield strength 40020 PSI, elongation 14%

The 6061-T651 seamless extruded aluminum tube used for the cylindrical portion of the vacuum chamber is also from A. M. Castle/Kaiser Aluminum. Test results: tensile strength 40,400 PSI or greater, yield strength 39,300 PSI or greater, elongation 16.5% or smaller.

The AZ31B-H24 magnesium sheet for the neutron beam windows are from Copper and Brass Sales, 6555 E. Davidson, Detroit, MI 48212-1499, (847)-490-9870. Test results: tensile strength 42,400 PSI, yield strength 31,200, elongation 15%.

All pieces meet appropriate AMS/ASME/ASTM specifications.

Pressure tests

The assembled chamber with windows was pressurized to 70 psi successfully. The inner domes were pressure tested to 80 psi and the outer domes to 117 psi.

Helium Leak tests

leak testing of the assembled chamber, the main weldment, and the magnesium domes were performed with a helium leak detector on the 1-10 E-9 cc/sec scale, no leaks found

Radiography

Note that due to the nature of the welds for this vessel radiography is not required according to the ASME code and as approved in a Change Control Request to the LANL safety committee. Nevertheless we went ahead and performed radiography anyway. The vendor was Calumet Testing Services, 1945 N. Griffith Blvd., Griffith, IN 46319, (219)-923-9800, (708)-474-5860. Xray radiographs were performed with xray source internal and external to the vessel in specified geometries referenced to stamped letters on the outside of the vessel. As expected the radiographs show the inclusions which are due to the helium gas channels required by the safety committee.

subsequent history

Later work at Indiana uncovered a leak in one of the internal welds. This weld was redone by a certified welder from Ability Engineering and is now helium leak-tight.

(2) Titanium Target Chamber

Excelco Development Inc.

65 Main Street
P.O. Box 230
Silver Creek, NY 14136
(716)-934-2651
fax(716)-934-9246

This liquid hydrogen vessel is an all-titanium cylindrical welded chamber with one inlet and one outlet port with Conflat-type seals. The shape of this vessel was chosen to reduce potential stress concentrations during various accident scenarios based on the results of finite-element analysis calculations performed by ARES Corporation, a LANL contractor.

Materials certification

The Grade-2 titanium bar and billet stock is from TICO Titanium, 52900 Grand River Avenue, New Hudson, MI 48165 (248)-446-0400, 1-800-521-4392, fac (248)- 446-1995. Test results for the lot: tensile strength 67,400 PSI or greater, yield strength 52300 PSI or greater, elongation ~28%
Typical annealing treatment: 1200F, 1 hour air cool

Helium leak test

Leak test of the chamber was performed at Excelco using a helium leak detector with no leaks visible.

Fluorescent liquid inspection

A fluorescent liquid penetrant test was performed by Excelco to look for gross welding faults/crakcs. None were found.

Radiography:

The titanium vessel was radiographed by Excelco. No faults were found.

Heat Treatment

Heat treatment on the target vessel after fabrication was performed by Accu-Temp Heat Treating, INC, 2400 Racine St. , Racine, WI 53403, (262)-634-1905, fax (262)-634-9102.
The vessel was heated in an Argon atmosphere for 1 hour at 1292F and oxidized for 5 minutes at 1400F, then air cooled. This annealing procedure appears in table 3 of "TIMETAL 50A CP Ti" literature from TIMET corp. The oxidation procedure (5 minutes in air) appears in "Corrosion Resistance of Titanium," a technical manual of TIMET at http://www.timet.com/productsframe.html. Stacey Nyakana, a researcher at TIMET (708-566-4403) was consulted in the choice of this prodecure. The object of this treatment was to ensure the development of an oxide layer on the inside surface of the chamber to suppress the possibility of hydrogen entering into the titanium.

Post-treatment tests

Grade-2 Ti tensile-test samples were loaded to failure after they received the annealing and oxidation procedure designed to ensure the existence of a thick oxide layer on the inner Ti surface. The test results, both from the dry run and the run with the Ti vessel, confirmed
that the oxide layer formed was tough and adherent and that the mechanical properties of the Ti were not altered from those of annealed grade-2 Ti.

subsequent history

Vessel was helium leak tested at IUCF and thermally shocked via repeated immersion
in liquid nitrogen without detectable leak on the 1E-9 cc/sec scale. Vessel was then pressure tested to a pressure of XXX PSI successfully. As a double-check on the annealing-oxidation procedure, the annealing-oxidation procedure was performed at IUCF on seven Ti foil samples that ranged from 0.2 mil to 12.8 mil in thickness. The samples 1.5 mil and thicker remained ductile and had an

adherent oxide layer. The oxide layers formed were 200-330 microgram/cm2.

H_2 gas manifold

Figure 5: Gas Handling System

For operational details see appendix 3.

- **specifications (M. Snow, M. Gericke, 7-1-01, modified by B. Lozowski, XXX)**

Table 6 lists the main components of the H_2 gas handling system and their relevant properties. The plumbing will be constructed of stainless steel components with VCR connections of welded tubing.

Table 6: *Properties of major gas handling system components*

Gas Handling Components	Relevant Properties			Function
	Inlet and outlet pressures	Material/Type	Operating and cleaning temperature	
Flow rate meter	150 psia inlet and outlet	304 stainless steel	300 K	Measure H2 gas flow rate
Hydrogen gas purifier	150 psia inlet 15 psia outlet	304 stainless steel body, palladium leak		Remove all non-hydrogen components to sub ppm concentration
Liquid N2 cold trap/Ortho-para Converter	15 psia inlet 15 psia outlet	FeO powder, OFHC copper/304 SS container, porous copper inlet and outlet	77 K 150 ºC	Trap water vapor and other freezable contaminants. Partial conversion of gas to parahydrogen state.
Residual gas analyzer	10E-3 torr inlet	Quadrupole RGA	300 K	hydrogen gas purity, helium leak detection, gas monitoring of main vacuum
Turbopump	N/A		300 K	evacuate target, main vacuum,helium jacket, and gas handling panel

- **design and operation (M. Gericke, 7-1-01, modified by M. Snow, 8-15-03)**

Description of Gas Handling System

Introduction:

The gas handling system has two primary purposes: to transport the hydrogen from a holding tank to the cryostat while conditioning the gas and regulating and metering the flow, and to vent the hydrogen from the cryostat to a vent stack that conducts the hydrogen outside of the enclosed area under certain well-defined conditions. The gas system also has a monitoring function: the RGA on the system looks for hydrogen and helium in the residual gas of the main vacuum system. A diagram of the gas handling system is shown in Figure 2. The pressure ratings of all the components of the system are shown in Table XXX. The settings of the relief and check valves are listed in Table XXX.

The gas handling system connects the hydrogen bottles with the cryostat. The subsystem which conducts hydrogen gas into the target consists of three key components, which each play a part in conditioning the hydrogen or regulating or metering it as it flows into the cryostat. The major components are:

1) Pressure regulator (PR105): this regulator sets the fill pressure for the palladium leak purifier and is fed with a line that possesses a 10 SLPM restrictive orifice and is fed by lines with 20 micron filters to eliminate particulate contamination from the bottles.
2) Palladium leak (PRFR). The palladium purifier will be used to extract impurities such as N_2, Ne, CH_4, CO, CO_2 and others. Palladium has the property that hydrogen can diffuse (leak) through it, but other elements cannot. The palladium leak is a commercial device consisting of a palladium membrane that can be heated to increase the transmission rate of hydrogen. The temperature of the palladium membrane is raised to ~200C to achieve a flow rate of 10 SLPM. The operation of the membrane produces an outflow of hydrogen gas into a side port of 2.5 cc/sec which must be fed into the vent stack. The entrance to the purifier is guarded by an automatic valve (V114) which only opens under certain interlock conditions.
3) Cold Trap and Ortho/para converter (OPC): The cold trap consists of a cold trap and an ortho-para converter both held at liquid nitrogen temperature. The cold trap catches any non-hydrogen impurities emanating from the palladium purifier (occasionally the operation of this device can release small amounts of water vapor). The ortho-para converter consists of a 77K cell in which the hydrogen is exposed to a catalyst consisting of a fine powder. The purpose of the converter is to partially convert orthohydrogen into parahydrogen, which is the ground spin state of the hydrogen molecule.

In addition to the hydrogen filling portion of the GHS, there are five other major components to the system as follows:

1) The turbopump system which evacuates the main vacuum of the target. It can be isolated from the main vacuum with an automatic valve (V204) which is interlocked.
2) The turbopump system that evacuates the hydrogen target flask
3) The residual gas analyzer (RGA1) which can be used to monitor the main vacuum system for hydrogen and helium through an interlocked automatic valve (V207).
4) The relief system consisting of check valves in the GHS itself (RV104, RV201, RV103, RV101, RV401) and in the vent line (CKV101) along with rupture disks (RD202, RD201, RD101)

5) The non-hydrogen gas supply systems: a helium supply system to deliver helium gas to the helium chambers on the main vacuum system and an argon supply system to fill the main vacuum system for emergency venting of the liquid hydrogen in the even of a fire.

Operating Procedures: General Description

The gas system has four primary modes of operation: preparation and liquification of the hydrogen, steady-state monitoring, and warmup/expulsion of the liquid hydrogen. Preparation consists of the following steps:

1) The GHS/target should be grounded with a grounding strap and checked with an ohmmeter to ensure that there is no electric charge building up on the system which could produce a spark.
2) The target chamber and main vacuum system must be pumped down to a pressure of 10^{-4} Torr or lower.
3) The target chamber, main vacuum system, and GHS must be leak checked when under vacuum with a helium leak detector which has been verified to be in proper working order before and after the leak checks. Any detectable leaks must be corrected and verified to be leak tight before operation.
4) The hydrogen lines must be pumped and purged with helium gas before introducing hydrogen into the system.
5) Helium gas must be introduced into the target channels,
6) Argon gas must be loaded and ready for introduction in the event that a fast warmup of the target is required.
7) An oxygen monitor with warning signs and flashing warning lights at the edge of the oxygen depletion hazard area should be set up.
8) The enclosure must be posted with appropriate warning signs:
   a) Cryogens in use
   b) Flammable Gas (Hydrogen) in use; Smoking and Open Flames Prohibited
   c) Oxygen Depletion Possible

Filling of the hydrogen consists of the following steps:

1. Valves V107, V112, V110, V113, V111, V118, V119, V119A, V123, V122, V127, V306, and V119 would be closed, isolating the rest of the GHS system from the hydrogen.
2. Valves V105, V103, V1901, V106, V104, V102, V100, V110, V114, V207, V307, and V120 would be opened, allowing hydrogen to flow into the target vessel and liquefy and allowing the RGA to monitor the main vacuum system for leaks.

3. Filling continues until the flow meter (FM101), the pressure gauges (P106, PT105), and the thermometers (T6, T7) indicate that the hydrogen has filled the target and that the liquid level is between T6 and T7 on the outlet side.
4. The valves along the hydrogen path are closed in reverse order along the fill path and at each point the hydrogen gas which is about to be isolated between the valves is either pumped out or sent through the vent stack as required.

To vent the hydrogen, the refrigerators are turned off and (in cases where rapid boiloff is required) the main vacuum is filled with argon gas. The boiling hydrogen then passes through the relief valve RV104 to the vent line.

- **data sheets**
- **test results**

Test Results October 31, 2003

The Test: cleaning, cold cycling, and leak checking of two parts of the LH_2 plumbing internal to the NPDG vacuum vessel; cleaning and leak checking of two H_2 plumbing parts external to the vacuum vessel.

Purpose: to verify that these four welded, CF-flanged components of the LH2 target are leak tight

The Parts: 1) a tube with a 90º bend, a bellows, and a _-inch VCR side connection; 2) a short tube with a 90º bend (to be used in the external plumbing between a side connection of the 2.75"-CF cross in the vent line and a rupture disk); 3) a welded, S-shaped tube; 4) a transition piece between .75"-CF flanged and 4.5"-CF flanged components n the H_2 vent line

On this date, parts 1-4 were found to be He leak tight at rate of $\leq 1\times10^{-9}$ cc/s. The procedure followed was first to verify that parts 1-4 were leak tight at room temperature. Then, all were cleaned by submersion (2.5 minutes) in a solution of 25 % HNO_3 + 2 % HF + 73 % water, by volume. Another leak check followed a through rinse in hot tap water, a final rinse in de-ionized water, a wipe down to remove the passivating layer, and drying.
Parts 1-3 (seen L to R in the photos below) were then joined (with copper CF gaskets) and continuously connected to the leak checker during two cycles between room temperature and equilibrium in LN_2. At each end of the temperature range, liberal spraying with He failed to find a leak anywhere. At the end of the tests, a final check determined that the sensitivity of the leak checker had remained in calibration.

Tests Performed By: Bill Lozowski and Alan Eads

Ortho/para converters (M. Snow, 6-16-01. modified by B. Lozowski, XXX)

There are two ortho-para converters in the target system. One is on the gas handling system and operates at 77 K. The other is on the cold stage of the cryorefrigerator and doubles as the liquefaction region. We plan to use iron oxide in the GHP converter and chromic oxide (CrO_3) as the active converter material at 20K. Our choice of CrO_3 is based on the data of N. S. Sullivan et al. [22], which showed that CrO_3 is a more effective catalyst than the more commonly-used iron oxide.
In addition, CrO_3 is antiferromagnetic at low temperature and therefore should not disturb the magnetic environment of the experiment.

We do not intend to insulate the lines from the gas handling system o-p converter except perhaps with styrofoam. to prevent condensation of water vapor on the lines. Given the dryness of LANL, we expect that this may not be necessary either.

The idea is to use the o-p converter in the gas handling system to reduce the heat load on the refrigerator and speed up the fill time. If it does not work the only consequence is a somewhat longer LH2 fill. For that reason we do not see it as a safety issue.

- **specifications (M. Snow, 6-16-01, modified by B. Lozowski, XXX)**

Both converters will be enclosed in OFHC copper chambers with fine mesh to prevent converter material from reaching other regions. Both converters will be bakeable for reactivation. Table 7 lists the important properties of the two ortho-para converters, which are different.

Table 7: *Ortho-para converter data*

Ortho-Para Converter	Geometric and Thermodynamic Data			Geometry and Cooling
	Volume	Rate of Heat Removal	Operating Temperature and O/P Ratio	
Gas Handling System	500 cc		77 K->50%	Gas inlet and outlet. Liquid Nitrogen
Main Vacuum vent line	280 cc		17 K->99.95% para	Gas inlet, liquid condensed on top surface, drips into annular converter. Cryorefrigerator.

- **design (M. Snow, 4-11-01, modified by WMS 2-2-03)**

The ortho-para converter chamber which is operated on the 17 K cold head of the cryorefrigerator doubles as the liquid condensation chamber. The gas is liquefied at the top of the chamber by thermal contact with a grooved OFHC copper surface. The liquid drips down into the ortho-para converter in a separate chamber. The body of the converter is made of copper to allow the converter material to be heated for regeneration if necessary. The CrO_3 is prevented from leaving the annular region with fine wire mesh on the inlet and outlet tubes. The body of the converter is designed as a two-piece device to allow for the replacement of the converter if required.

- **data sheets**

- **test results**

Cryocoolers

- **specifications (M. Snow, 5-26-01, modified 12-16-02 by WMS)**

The cryorefrigerators will both be two stage closed-cycle refrigerators. One, made by CVI, is based on the Gifford McMahon cycle and possesses mechanical moving parts. The other, made by Cryomech and called a pulse-tube refrigerator, involves only the motion of helium gas. The operation of the CVI refrigerator is independent of their spatial orientation, whereas the Pulse-tube refrigerator orientation must be vertical.. The CVI refrigerator contains moving parts which were specially made of sufficiently nonmagnetic materials (nonmagnetic stainless is sufficient) so that the magnetic field in the experiment can be made with sufficient uniformity. Table 8 lists the relevant properties of the two cooling stages.

Table 8: *Properties of the two-stage cryorefrigerators*

Cooling Stage	Thermodynamic Data			Mechanical Data
	Cooling Power	Temperature Stability, no load	Operating Range	Frequency
Stage 1, 77K	60 W	0.5 K	77 K->300 K	1.2 Hz
Stage 2, 20K	12 W	0.5 K	11 K->300 K	1.2 Hz

- **cryostat design calculations (M. Snow, 4-10-01)**

Let us recall some of the basic facts about the properties of liquid hydrogen and its thermodynamics:

density: 0.071 g/cc
latent heat of vaporization: 444J/g
heat of ortho-para conversion: 709 J/g
specific heat of H2 gas: approx: 12 J/(g·K) from 20-300 K

The LH_2 volume of the target is 21 liters. This gives a target mass of 1.5 kg and corresponds to a total gas volume at room temperature and 1 bar pressure of 18 cubic meters. For this volume, 4300 kJ is required to cool the gas from 300 K to 80 K, 950 kJ is required to cool the gas from 80 K to 20 K, 665 kJ is required to liquify the gas at 20 K, 40 kJ is required to cool the liquid from 20 K to 17 K, and 1070 kJ is required to convert the gas to parahydrogen, with about a third of the heat of conversion released by 80 K. If we neglect the effect of the ortho-para conversion in the gas handling system and assume that all ortho-para conversion occurs in the condenser, then the 80K stage of the cryorefrigerator must remove 4835 kJ and the 17 K stage must remove 2190 J. Given the cooling power of one cryorefrigerator (60 watts at 80 K, 12 watts at 20K) and the radiative heat load on the 80 K and 17 K radiation shields (15 watts and 0.1 watts, respectively), then the liquification of the target takes 2 days, with the rate set by the cooling power of the 17 K cooling stage. This corresponds to a gas flow rate in the gas handling system of about 10 standard liters/minute.

The radiative heat loads on the radiation shields quoted above are calculated using the usual Stefan-Boltzmann law asuming a geometry of concentric cylinders, an emissivity of 0.02, and temperatures for the radiating surfaces of 300 K, 150 K, and 17 K. The second cryorefrigerator will easily be able to remove the 0.1 watt heat load on the inner radiation shield.

The radiation shields and the thermal connection to the target chamber will be made of OFHC copper. Given the thermal conductivity of copper (20 W/(cm·K) at 20 K), one can estimate the required cross sectional area of the thermal connection to the target as follows. For the liquid target, assume that the refrigerator is operated at a temperature two degrees lower (15 K) than the target temperature (17K). (This is safely above the solidification temperature of liquid hydrogen at a pressure of 1/3 bar of 14 K). Furthermore, assume that one requires a cooling power 5 times the expected radiative heat load on the target without the operation of the second refrigerator, or 0.5 W. (In fact, with the operation of the second cryorefrigerator cooling the radiation shield to a temperature below 17 K, the dominant heat load on the target is due to the thermal conductance of the liquid hydrogen itself in contact with the warmer vapor in the exhaust line and the thermal conductance of the exhaust line tubing. Given the small conductivities involved [liquid H_2: 1.2 mW/(cm·K), gaseous H_2: 0.15 mW/(cm·K), stainless steel in the exhaust line: 10 mW/(cm·K)], the expected heat load from this source is on the order of tens of mW. Heat due the the neutron beam capture and gamma loss in the taregt is at the few microwatt level) Then the required ratio of area to length for the thermal connection in this extreme case is

(area/length)=0.5W/([20W/cm*K]*2K)=0.0125 cm

For a length of 20 cm for the thermal connection between the refrigerator and target, this gives a cross sectional area of 0.25 cm^2. This cross sectional area can easily be supplied using copper braid.

- **data sheets (M. Snow)**

The Appendix includes a plot of the cooling power of the two stages of the CVI CGR511 refrigerator and the Cryomech XXX refrigerator which will be used to liquefy and convert the hydrogen.

- **test results**

The following is the report of the cryogenic tests done at Indiana before shipment to Los Alamos.

dear NPDG collaborators:

As you may know the liquid hydrogen target system that has been designed and constructed at IUCF is slated to arrive at LANL on Monday Aug. 18. In this note I want to give the collaboration a brief description of the system and its cryogenic performance based on recent tests. The bottom line is that the taregt/refrigerator system works well from a cryogenic point of view.

First a guided tour of some pictures of various parts of the apparatus which can be accessed at http://www.iucf.indiana.edu/~snow/NPDGamma.

Image 004 is an (almost) succcessful attempt to include all elements of the system in one picture. Visible are, from left to right, (1) the front edge of the LH2 main vacuum system, (2) the two helium compressors for the 2 mechanical refrigerators, (3) the pumping/gas handling system, and (4) a rack with the PLC control system and pressure/temperature measurement.

Images 002 and 010 are different views of the target main vacuum on the Manitoba stand.
In image 002 at the bottom you can see a part of the aluminum LH2 target chamber. This
chamber finally arrived this week. It successfully passed an pressure test at 90 psia and helium leak check and will be cooled down at LANL. Image 010 shows a rear view of the chamber with the Cryomech pulse tube refrigerator on top.

Images 001 and 007 are front and side views of the gas handling/pumping system.
The residual gas analyzer is the gray box mounted vertically near the center of the picture.
Two turbopumps lie on the other side of the panel. In image 007 the palladium membrane hydrogen purifier at upper left is resting on top of the turbopump control: on the right one can see the liquid nitrogen-cooled cold trap and orth-para converter to partially pre-convert the hydrogen gas and reduce the heat load on the cryogenic system which rests on a separate stand that allows us to drop the dewar.

Image 005 shows the control system rack. The PLC display is at the top with a schematic display of the gas/target system with its status. Lower are the pressure and temperature gauges and controls.

Image 009 shows the helium compressors for the two refrigerators mounted on a common rack and the flexible metal hoses that connect to the refrigerators.

To test the thermal performance of the cryogenic system under an almost "worst-case" situation we assembled and conducted a test cooldown under the following conditions, which I relate in detail for those who may be interested and will supplement with more images later (others can skip to the punchlines below). First we installed the titanium taregt chamber into the vessel. Titanium has a much worse thermal conductivity than the aluminum vessel we plan to use for the experiment. Then we separated the titanium vessel from the surrounding copper radiation shield by plastic with poor thermal conductivity similar to that for the lithium-loaded plastic that will surround the taregt vessel. The thermal connection between the refrigerator and the taregt consisted only of a copper clamp at the rear of the taregt which did not directly touch the target vessel at all: only the copper radiation shield outside of it. This radial clamp is soldered onto a soft copper bar which was bent by 90 degrees at the downstream end of the vacuum chamber for thermal connection to the cold stage of the Cryomech pulse tube cryorefrigerator. Therefore the thermal connection to the taregt itself was relatively poor but preserved the possibility of hermetically surrounding the entire taregt vessel with neutron shielding everywhere except the entrance and exit of the neutron beam. The outside of the copper shield was covered with low-emissivity aluminum tape. The chamber was centered inside the polished cylindrical ~80K copper shield with a G-10 plastic centering ring. The 80K copper shield was in thermal contact with both the cryorefrigerators. The outside of the 80K shield was wrapped in about 30 layers of superinsulation consisting of Mylar coated on both sides with aluminum and with layers separated with thin plastic netting and periodic small hoels for easier evacuation of gas between layers. The 80K shield was thermally isolated from the inside surface of the main vacuum with two G-10 spacers. The neutron beam entrance windows consisted of thin aluminum taped to the copper with copper tape. The target fill line was connected to an ortho-para converter chamber in thermal contact with the lower CVI mechanical refrigerator and from there to the H2 liquification chamber in thermal contact with the Cryomech pulse tube refrigerator. The vent line was not installed for this test since it is being welded together now: this is the reason for the "almost" in the first sentence above. However it is nonmag stainless steel and we estimate that the additional heat load that it delivers to the taregt is small compared to the other sources present in the system. Finally the entire inner surface of the aluminum vacuum chamber was polished to an almost mirror finish to reduce emissivity using alumina powder and one of those buffer wheels that people use to polish cars.

Under these conditions and with both refrigerators operating, the temperature of the titanium
taregt vessel as measured by a thermometer at the farthest point from the refrigerator reached 9.4K. The temperature of the cold stage of the Cryomech refrigerator as measured at the farthest point away from the titanium vessel reached 8.25K.
Implications are that (1) we will have no problem reaching the operating temperature of 17K with heaters, (2) the overall heat load on the Cryomech cold stage based on its final temperature is a few watts, consistent with expectations, and can be decreased further with more superinsulation, (3) there is an upper bound on the thermal gradient across the target of 1.15K, the real gradient is probably smaller than this by at least an order of magnitude and will be smaller still in the aluminum vessel, which means that we expect that the aluminum vessel would have reached in the same test a temperature between 8.25 and 9.4K (4) we will not require a direct thermal contact between the liquid hydrogen taregt vessel and the copper cold finger, the plastic neutron shiedling will be able to surround the sides of the vessel in a hermetic fashion. There will be some more thermal contact between the taregt vessel and the refrigerator through clamps on the exit line and so again we would expect the taregt temperature to be lowered with this addition. These effects will compensate for the increase in thermal load when the taregt vent line is connected and full of hydrogen gas.

WE then turned off the CVI mechanical refrigerator and determined whether or not the Cryomech pulse tube refrigerator was capable of maintaining the taregt temperature at a low enough value by itself after the initial cooldown. The asymptotic values of the taregt temperature and the Cryomech cold stage in this case were 13K and 11K, respectively. This is very encouraging because it means that, during data taking, we may be able to turn off the CVI mechanical refrigerator completely. This would be good because the operation of the CVI refrigerator introduces mechanical vibrations into the system which we would like to avoid. The Cryomech refrigerator

introduces no detectable vibrations to the vacuum system. WE would then use the CVI mechanical refrigerator only for the initial liquification and ortho-para conversion of the hydrogen (the o-p conversion heat is comparable to the liquification heat and is significant).
To do this we may need to introduce an additional thermal link between the Cryomech and the ortho-para converter to keep it cold enough. This can be done easily with copper braid and will be the subject of further cryogenic tests at LANL.

LH_2 Target Instrumentation (M. Snow, 4-22-01)

The instrumentation required for the operation of the liquid hydrogen target can be divided into systems internal to and external to the main vacuum system. Inside the vacuum system, the instrumentation consists of thermometry in the target vacuum and pressure gauges in the GHS. Outside the system, the instrumentation consists of gas sensors inside the cave to detect hydrogen.

Table 9 lists the in-vacuum instrumentation and its technical requirements.

Table 9: *Instrumentation associated with target operation.*

Instrument	Transducer Requirements			Mechanical Data
	Locations	Operating Range	Accuracy	Reproducibility
Thermometers	LH_2 target, O/P converter, cryorefrigerator stages, radiation shields, target outlet. No thermometers inside LH_2 chamber	10-300 K on target, second stage of refrigerators, O/P converter, cold radiation shield. 70-300 K on warm radiation shield, first stage of refrigerators	0.2 K accuracy in 10-30 K range, 2 K accuracy in 70-300K range	0.1 K in 10-30 K range, 2 K in 70-300 K range
Pressure Gauges	LH_2 target, main vacuum, He jacket. All located on GHP external to cave	2->10E-7 bar on main vacuum and LH_2 target. 2->10E-3 bar on He jacket	11 K->300 K	3% near atmospheric pressure
Heaters	LH_2 target, O/P converter, cryorefrigerator stage 2, target outlet at liquid-vapor phase boundary.	0-several watts		

- **specifications**
- **design (M. Snow, 4-22-01)**

The pressure gauges and thermometers are commercially available components.

NPDGamma Temperature Controller Connection Details

Destination controller or monitor	***Name of the sensor***	***Cable no.***	***Wire***	***Signal***	***50-pin #***	***Destination pin no.***
Lakeshore 218 channel 1-4 DB25	T1		Black	I+	3	3
			Red	I-	1	15
			White	V+	4	4
		104239	Green	V-	2	16
	T4		Black	I+	15	6
			Red	I-	13	18
			White	V+	16	7
		104242	Green	V-	14	19
	T5		Black	I+	20	9
			Red	I-	18	21
			White	V+	21	10
		104245	Green	V-	19	22
Lakeshore 218 channel 5-8 DB25	T8		Black	I+	32	3
			Red	I-	30	15
			White	V+	33	4
		104246	Green	V-	31	16
	T9		Black	I+	36	6
			Red	I-	34	18
			White	V+	37	7
		104247	Green	V-	35	19
	T10	104248	Black	I+	40	9

Destination controller or monitor	***Name of the sensor***	***Cable no.***	***Wire***	***Signal***	***50-pin #***	***Destination pin no.***
			Red	I-	38	21
			White	V+	41	10
			Green	V-	39	22
Lakeshore DRC-91C 5-pin channel 1	T6	104243	Black	I+	24	A
			Red	I-	22	B
			White	V+	25	E
			Green	V-	23	D
Lakeshore DRC-91C 5-pin channel 2	T7	104244	Black	I+	28	A
			Red	I-	26	B
			White	V+	29	E
			Green	V-	27	D
Lakeshore DRC-91C Heater	H4	Not assigned	Red & Black	I+	45	
			White & Green	I-	46	
Scientific Instruments 9600 unit#1	T2	104240	Black	I+	7	
			Red	I-	5	
			White	V+	8	
			Green	V-	6	
	H1	Not assigned	Red & Black	I+	42	

Destination controller or monitor	***Name of the sensor***	***Cable no.***	***Wire***	***Signal***	***50-pin #***	***Destination pin no.***
			White & Green	I-	43	
Scientific Instruments 9600 unit#2	T3		Black	I+	11	
			Red	I-	9	
			White	V+	12	
		104241	Green	V-	10	
	H3	Not assigned	Red & Black	I+	49	
			White & Green	I-	50	

Sensor Name	Sensor Signal Name	Sensor Signal Wire Color	Lakeshore DB25 Connector (Channels 1 - 4)	Lakeshore DB25 Connector (Channels 5 - 8)	Lakeshore 5-pin Connector	New Controller connector	Cable Number
T1	I-	Red	15				**104239**
T1	V-	Green	16				
T1	I+	Black	3				
T1	V+	Yellow	4				
T2	I-	Red				TBD	**104240**
T2	V-	Green				TBD	
T2	I+	Black				TBD	
T2	V+	Yellow				TBD	
T3	I-	Red				TBD	**104241**
T3	V-	Green				TBD	
T3	I+	Black				TBD	
T3	V+	Yellow				TBD	
T4	I-	Red	24				**104242**
T4	V-	Green	25				
T4	I+	Black	12				
T4	V+	Yellow	13				
T5	I-	Red		15			**104243**
T5	V-	Green		16			

T5	I+	Black		3			
T5	V+	Yellow		4			
T6	I-	Red			B		**104244**
T6	V-	Green			D		
T6	I+	Black			A		
T6	V+	Yellow			E		
T7	I-	Red			B		**104245**
T7	V-	Green			D		
T7	I+	Black			A		
T7	V+	Yellow			E		
T8	I-	Red		18			**104246**
T8	V-	Green		19			
T8	I+	Black		6			
T8	V+	Yellow		7			
T9	I-	Red		21			**104247**
T9	V-	Green		22			
T9	I+	Black		9			
T9	V+	Yellow		10			
T10	I-	Red		24			**104248**
T10	V-	Green		25			
T10	I+	Black		12			
T10	V+	Yellow		13			

Details of the Pressure Transducers

Table1: Range and type of the pressure transducers.

Name of the trans.	*Type / Model*	*Output range (Volt)*	*Pressure range (Psia)*	*Pressure range (bar)*	*Input address in PLC*	*ADC input range (Volt)*
PT101	OMEGA PX203-030A5V	0.5 – 5.5	0-30	0-2.068	I:2.0	0-10
PT102	Millipore NTT205	0.05-5.05	0-500	0-34.48	I:2.1	0-10
PT103	OMEGA PX203-030A5V	0.5-5.5	0-30	0-2.068	I:2.2	0-10
PT104	MKS 722A14TCE2FJ	0.0-10.0	0-193.4	0-13.335	I:2.3	0-10
PT105	OMEGA PX303-100A5V	0.5-5.5	0-100	0-6.895	I:2.4	0-10
PT106	OMEGA PX303-050A5V	0.5-5.5	0-50	0-3.448	I:2.5	0-10
PT201	OMEGA PX303-050A5V	0.5-5.5	0-50	0-3.448	I:2.6	0-10
PT202	MKS 122AA-10000BB	0.0-10.0	0-193.4	0-13.335	I:2.7	0-10
PT203	OMEGA PX303-050A5V	0.5-5.5	0-50	0-3.448	I:3.0	0-10
PT301	Balzers				I:3.1	0-10

Name of the trans.	*Type / Model*	*Output range (Volt)*	*Pressure range (Psia)*	*Pressure range (bar)*	*Input address in PLC*	*ADC input range (Volt)*
	compact Pirani Gauge TPR250					
PT302	Balzers compact full range gauge PKR250	0.0-10.0		$5x10^{-12}$ – 1.0	I:3.2	0-10
PT303	MKS sensavac Series 941	0.0-8.0 1V offset		$1.3x10^{-13}$ – $1.3x10^{-5}$	I:3.3	0-10

Table2: Voltage & flow range and type of the flowmeters.

Name of flowmeter	*Model Number*	*Output range (Volt)*	*Flow range (SLPM)*	*Input address in PLC*	*ADC input range (Volt)*
FM101	822S-L-8-OV1-PV1-V1-HP	0.0-5.0	0-15	I:3.4	0-10
FM401	822S-L-8-OV1-PV1-V1-HP	0.0-5.0	0-15	I:3.5	0-10

Table3: Wirings and voltage details of the transducers.

Name of the transducer	*Required Excitation (Volt)*	*Actual voltage applied (Volt)*	*Source of the power*	*Wirings details (from device to gauge panel meter). Name tag attached to cables*	*Cable no. (from guage meter to PLC analog I/O)*
PT101	+(7-35) VDC	+12 VDC	Omega panelmeter	Red-> Excitation Black->Common	104226

Name of the transducer	***Required Excitation (Volt)***	***Actual voltage applied (Volt)***	***Source of the power***	***Wirings details (from device to gauge panel meter). Name tag attached to cables***	***Cable no. (from guage meter to PLC analog I/O)***
				White->Signal	
PT102	+(11-30) VDC	+12 VDC	Omega panelmeter	Red -> Excitation (+) Black-> Excitation (-) Green(white)-> Signal(+) Bare -> Shield	104227
PT103	+(7-35) VDC	+12 VDC	Omega panelmeter	Red-> Excitation Black->Common White->Signal	104228
PT104	+(13-32) VDC	+12 VDC	MKS panelmeter	Green -> Power in Red -> Signal (+) Black -> Signal (-) White-> Power return	104229
PT105	+(9-30) VDC	+12 VDC	Omega panelmeter	Red-> Excitation Black->Common White->Signal	104230
PT106	+(12-32) VDC	+12 VDC	Omega panelmeter	Red-> Excitation Black->Common White->Signal	Not assigned
PT201	+(12-32) VDC	+12 VDC	Omega panelmeter	Red-> Excitation Black->Common White->Signal	104231

Name of the transducer	*Required Excitation (Volt)*	*Actual voltage applied (Volt)*	*Source of the power*	*Wirings details (from device to gauge panel meter). Name tag attached to cables*	*Cable no. (from guage meter to PLC analog I/O)*
PT202	+15 and -15 VDC	+15 and -15 VDC	Local made aluminum box	Cable1: White -> Signal(+) Black -> Signal (-) Cabl2: +/- 15 VDC	104232
PT203	+(12-32) VDC	+12 VDC	Omega panelmeter	Red-> Excitation Black->Common White->Signal	104233
PT301	115 VAC	115 VAC	Power panel		104234
PT302					104235
PT303	115 VAC	115 VAC	Power panel	Special cable	104236
FM101	+15 VDC	+15 VDC	Local made aluminum box	Red-> Excitation Black->Common Green->Signal	104237
FM401	+15 VDC	+15 VDC	Local made aluminum box	Red-> Excitation Black->Common Green->Signal	104238

The pressure transducers (PT101, PT102, PT103, PT104, PT105, PT106, PT201, PT202 and PT203) have been calibrated using two known pressures i) vacuum (assumed to be zero pressure) and ii) atmospheric pressure of LANL (which is taken as 777 mbar). The voltage readings are taken at different times and different days in order to check their stability. The average voltages corresponding to the above pressures, and the calibration parameters for each of the transducers is given in the table below.

Name of pressure	Voltage measured at zero mbar	Voltage measured at 777	Slope m, in P=mV+c	c, the offset in the fit

transducer	(Volts)	mbar (Volts)		
PT101	0.135	2.041	0.40766	-0.055
PT102	0.022	0.0885	11.6842	-0.257
PT103	0.512	2.427	0.40574	-0.2077
PT104	-0.029	0.573	1.2907	+0.0374
PT105	0.513	1.084	1.3608	-0.698
PT106	0.501	1.645	0.6792	-0.3403
PT201	0.513	1.670	0.6716	-0.3445
PT202	-0.006	0.577	1.33276	+0.008
PT203	0.514	1.668	0.6733	-0.3461

- **test results**

- **hydrogen detectors**
  - **specifications**
  - **design**
  - **data sheets**
  - **test results**

System Operation and Safety Controls (M. Snow, 5-6-01)

We propose to provide an Allen-Bradley Logic Controller (SLC) for operation of the target. The SLC performs the monitoring and communications with all of the transducers for the target. The control software provides an operator with a computer interface with real-time control and data acquisition in both text and graphical format. All parts of the system will be depicted with animation that can display graphically all signals, both in real-time mode and in a historical mode. An information page of the status of the system will be created for network communications to be sent both to the NPDG DAQ and to the LANSCE CCR.

We furthermore propose a separate safety control system. This system would be concerned with the monitoring of only those transducer signals, which are associated with target safety. It would monitor safety-sensitive signals and operate devices such as fans associated with hydrogen safety. It would be interlocked in an appropriate manner with the LANSCE safety systems.

The SLC system implements 30-ft wire runs between the I/O of the SLCs and the components of the gas handling system (GHS) to maintain flexibility in location of the SLC. The Panel View display pages allow control of the 6 normally closed solenoid valves located in the GHS and display the following components:

a) H2 system (1xx),
b) Main Vacuum System (2xx),
c) RGA System (3xx), and
d) He System (4xx),
e) Temperature sensor values and graphic display of the sensor locations (9, to be supplied),
f) Pressure values indicated by the 9 Omega PTs (0.5-5.5V output signals),
g) Readout of the 2 mass-flow meters (FM401 and FM101),
h) Valve-control interlocks (activated by PT setpoints), and override controls.

Closed/Not-Closed indication of 22-25 manual round-knob valves will be implemented via one microswitch and 2 LEDs attached to each valve. If the LEDs are powered with a 9V supply placed near the valves, the voltage polarity reversal across the microswitch when it changes state may be used by the SLC. This arrangement allows 2-conductor hookup for each valve.

The SLC interfaces with the temperature output signals of 7 silicon diodes (standard curve 10) activated and monitored by the Lakeshore 215 8-channel sensor monitor and the Scientific Instruments XXX. It also interfaces with the Lakeshore DRC-91C Temperature Controller to: obtain the temperatures indicated by 2 silicon-diode sensors and Adjust the control setpoint of the unit.

During power outages of less than 20 minutes, the control system must continue to monitor and display (View Panel) the target pressures and temperatures. Beyond 20 minutes, the SLC must shut down gracefully. This is ensured through the use of 4 UPSs.

- **specifications**

DEVICE	STATUS?	CONTROL?	STATUS Signal Type	CONTROL Signal Type	Qty. - Discrete Inputs	Qty. - Discre Outpu
[redacted]	YES	NO	+24VDC - Discrete	n.a.	2	000
[redacted]	YES	NO	+24VDC - Discrete	n.a.	2	000
[redacted]	YES	NO	+24VDC - Discrete	n.a.	2	000
[redacted]	YES	NO	+24VDC - Discrete	n.a.	2	000
[redacted]	YES	NO	+24VDC - Discrete	n.a.	2	000
[redacted]	YES	NO	+24VDC - Discrete	n.a.	2	000
[redacted]	YES	NO	+24VDC - Discrete	n.a.	2	000

[redacted]	YES	NO	+24VDC - Discrete	n.a.	2	000
	YES	NO	+24VDC - Discrete	n.a.	2	000
	YES	YES	+24VDC - Discrete	+24VDC - Discrete	2	
	YES	NO	+24VDC - Discrete	n.a.	2	000
	YES	NO	+24VDC - Discrete	n.a.	2	000
	YES	NO	+24VDC - Discrete	n.a.	2	000
	YES	NO	+24VDC - Discrete	n.a.	2	000
	YES	NO	+24VDC - Discrete	n.a.	2	000
	YES	NO	+24VDC - Discrete	n.a.	2	000
[redacted]	YES	NO	+24VDC - Discrete	n.a.	2	000
	YES	NO	+24VDC - Discrete	n.a.	2	000
	YES	NO	+24VDC - Discrete	n.a.	2	000
	YES	NO	+24VDC - Discrete	n.a.	2	000
	YES	NO	+24VDC - Discrete	n.a.	2	000
	YES	NO	+24VDC - Discrete	n.a.	2	000
	YES	NO	+24VDC - Discrete	n.a.	2	000
	YES	NO	+24VDC - Discrete	n.a.	2	000
[redacted]	YES	YES	+24VDC - Discrete	+24VDC - Discrete	2	
	YES	NO	+24VDC - Discrete	n.a.	2	000

[redacted]	YES	NO	+24VDC - Discrete	n.a.	2	000
[redacted]	YES	YES	+24VDC - Discrete	+24VDC - Discrete	2	
[redacted]	YES	NO	+24VDC - Discrete	n.a.	2	000
[redacted]	YES	YES	+24VDC - Discrete	+24VDC - Discrete	2	
[redacted]	YES	NO	+24VDC - Discrete	n.a.	2	000
[redacted]	YES	NO	+24VDC - Discrete	n.a.	2	000
[redacted]	YES	NO	+24VDC - Discrete	n.a.	2	000
[redacted]	YES	NO	+24VDC - Discrete	n.a.	2	000
[redacted]	YES	YES	+24VDC - Discrete	+24VDC - Discrete	2	
[redacted]	YES	NO	+24VDC - Discrete	n.a.	2	000
[redacted]	YES	NO	+24VDC - Discrete	n.a.	2	000
[redacted]	YES	NO	+24VDC - Discrete	n.a.	2	000
[redacted]	YES	NO	+24VDC - Discrete	n.a.	2	000
[redacted]	YES	NO	+24VDC - Discrete	n.a.	2	000
PT204 (Press. Xducer - CCG)	YES	YES	ANALOG	Relay Contacts	000000	000
PT301 (Press. Xducer - Diaphram)	YES	NO	ANALOG	n.a.	000000	000
PT302 (Press. Xducer - CCG)	YES	YES	ANALOG	Relay Contacts	000000	000
PT401 (Press. Xducer - Diaphram)	YES	NO	ANALOG	n.a.	000000	000
PT402 (Press. Xducer - Diaphram)	YES	NO	ANALOG	n.a.	000000	000

FM101 (Flow Meter - Mass)	YES	NO	ANALOG	n.a.	000000	000
FM401 (Flow Meter - Mass)	YES	NO	ANALOG	n.a.	000000	000
Lakeshore Temp Setpoint Mon.	YES	NO	ANALOG	n.a.	000000	000
PT101 (Press. Xducer - Diaphram)	YES	NO	ANALOG	n.a.	000000	000
PT102 (Press. Xducer - Diaphram)	YES	NO	ANALOG	n.a.	000000	000
PT103 (Press. Xducer - Diaphram)	YES	NO	ANALOG	n.a.	000000	000
PT104 (Press. Xducer - Diaphram)	YES	NO	ANALOG	n.a.	000000	000
PT105 (Press. Xducer - Diaphram)	YES	NO	ANALOG	n.a.	000000	000
PT201 (Press. Xducer - Diaphram)	YES	NO	ANALOG	n.a.	000000	000
PT202 (Press. Xducer - BARATRON)	YES	NO	ANALOG	n.a.	000000	000
PT203 (Press. Xducer - Diaphram)	YES	NO	ANALOG	n.a.	000000	000
RGA1 (Residual Gas Analyzer)	YES	YES	RS-232	RS-232	000000	000

Distribution of pins of the 37-pin connectors

Table 1: Pin distribution for Jconn-1 connector

Pin no.	*Description of the connection*	*Cable no. (from 37-pin to PLC)*	*Wiring details from device to connector*
1	V100 open switch-sink	104191	
2	V100 open switch-24 VDC	104191	
3	V100-solenoid	104192	
4	V100-solenoid	104192	
5	V114 open switch-sink	104193	Red -> Common
6	V114 open switch-24 VDC	104193	Black -> N.C.
7	V114-solenoid	104194	Black -> 24 VDC
8	V114-solenoid	104194	Black -> Ground
9	V201 open switch-sink	104195	Not available
10	V201 open switch-24 VDC	104195	Not available

Pin no.	***Description of the connection***	***Cable no. (from 37-pin to PLC)***	***Wiring details from device to connector***
11	V201-solenoid	104196	Black -> 24 VDC
12	V201-solenoid	104196	Black -> Ground
13	V204 open switch-sink	104197	Green -> Common
14	V204 open switch-24 VDC	104197	White -> N.O.
15	V204-solenoid	104198	Red -> 24 VDC
16	V204-solenoid	104198	Black -> Ground
17	V205 open switch-sink	104199	Red -> Common
18	V205open switch-24 VDC	104199	Black -> N.O.
19	V205-solenoid	104200	Black -> 24 VDC
20	V205-solenoid	104200	Black -> Ground
21	V207 open switch-sink	104201	Red -> Common
22	V207 open switch-24 VDC	104201	White -> N.O.
23	V207-solenoid	104202	Green -> 24 VDC
24	V207-solenoid	104202	Brown -> Ground
25	V303 open switch-sink	104203	Not available
26	V303 open switch-24 VDC	104203	Not available
27	V303-solenoid	104204	Black -> 24 VDC
28	V303-solenoid	104204	Black -> Ground
29	V129-solenoid	No number	Red -> 24 VDC
30	V129-solenoid	No number	Black -> Ground
31			
32			
33			
34			
35			
36			
37	24 VDC power	104482	

Table 2: Pin distribution for Jconn-3A connector

Pin no.	*Description of the connection*	*Cable no. (from 37-pin to PLC)*	*Wiring details from device to connector*
1	V107 open switch-sink	104205	Green -> Common
2	V107 open switch-24 VDC	104205	White -> N.O.
3	V108 open switch-sink	104206	Green -> Common
4	V108 open switch-24 VDC	104206	White -> N.O.
5	V109 open switch-sink	104207	Green -> Common
6	V109 open switch-24 VDC	104207	White -> N.O.
7	V110 open switch-sink	104208	Green -> Common
8	V110 open switch-24 VDC	104208	White -> N.O.
9	V111 open switch-sink	104209	Green -> Common
10	V111 open switch-24 VDC	104209	White -> N.O.
11	V113 open switch-sink	104210	Green -> Common
12	V113 open switch-24 VDC	104210	White -> N.O.
13	V115 open switch-sink	104211	Green -> Common
14	V115 open switch-24 VDC	104211	White -> N.O.
15	V117 open switch-sink	104212	Green -> Common
16	V117 open switch-24 VDC	104212	White -> N.O.
17	V119 open switch-sink	104213	Green -> Common
18	V119 open switch-24 VDC	104213	White -> N.O.
19	V120 open switch-sink	104214	Green -> Common
20	V120 open switch-24 VDC	104214	White -> N.O.
21	V121 open switch-sink	104215	Green -> Common
22	V121 open switch-24 VDC	104215	White -> N.O.
23	V122 open switch-sink	104216	Green -> Common
24	V122 open switch-24 VDC	104216	White -> N.O.
25	V125 open switch-sink	104217	Green -> Common

Pin no.	***Description of the connection***	***Cable no. (from 37-pin to PLC)***	***Wiring details from device to connector***
26	V125 open switch-24 VDC	104217	White -> N.O.
27	V126 open switch-sink	104218	Green -> Common
28	V126 open switch-24 VDC	104218	White -> N.O.
29	V128 open switch-sink	104219	Green -> Common
30	V128 open switch-24 VDC	104219	White -> N.O.
31	V208 open switch-sink	104220	Green -> Common
32	V208 open switch-24 VDC	104220	White -> N.O.
33	V302 open switch-sink	104221	Green -> Common
34	V302 open switch-24 VDC	104221	White -> N.O.
35			
36			
37	24 VDC power	104483	

Table 3: Pin distribution for Jconn-3B connector

Pin no.	***Description of the connection***	***Cable no. (from 37-pin to PLC)***	***Wiring details from device to connector***
1	V304 open switch-sink	104222	Green -> Common
2	V304 open switch-24 VDC	104222	White -> N.O.
3	V403 open switch-sink	104223	
4	V403 open switch-24 VDC	104223	
5	V502 open switch-sink	104224	
6	V502 open switch-24 VDC	104224	
7	V504 open switch-sink	104225	
8	V504 open switch-24 VDC	104225	
9	V129 open switch-sink	104292	Green -> Common

Pin no.	***Description of the connection***	***Cable no. (from 37-pin to PLC)***	***Wiring details from device to connector***
10	V129 open switch-24 VDC	104292	White -> N.O.
11	V119A open switch-sink	104478	Green -> Common
12	V119A open switch-24 VDC	104478	White -> N.O.
13	LN2 open switch-sink	104479	
14	LN2 open switch-24 VDC	104479	
15	H2 ALARM open switch-sink	104480	
16	H2 ALARM open switch-24 VDC	104480	
17	He-RGA set open switch-sink	104481	
18	He-RGA set open switch-24 VDC	104481	
19			
20			
21			
22			
23			
24			
25			
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27			
28			
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31			
32			
33			
34			
35			
36			

Pin no.	***Description of the connection***	***Cable no. (from 37-pin to PLC)***	***Wiring details from device to connector***
37	24 VDC power	104484	

PLC ADDRESSES

Table 1: Open switch status input addresses at PLC.

Address in PLC	***Name of the valve***	***Wire to the sink of discrete input module***	***Wire to the 24 VDC of discrete input module***	***Cable no. (from 37-pin to PLC discrete I/O)***
I:1.0/00	V100	Red	Green	104191
I:1.0/02	V114	Red	Green	104193
I:1.0/04	V201	Red	Green	104195
I:1.0/06	V204	Red	Green	104197
I:1.0/08	V205	Red	Green	104199
I:1.0/10	V207	Red	Green	104201
I:1.0/12	V303	Red	Green	104203
I:1.0/14	V107	Red	Green	104205
I:1.1/00	V108	Red	Green	104206
I:1.1/02	V109	Red	Green	104207
I:1.1/04	V110	Red	Green	104208
I:1.1/06	V111	Red	Green	104209
I:1.1/08	V113	Red	Green	104210
I:1.1/10	V115	Red	Green	104211
I:1.1/12	V117	Red	Green	104212
I:1.1/14	V119	Red	Green	104213
I:1.2/00	V120	Red	Green	104214
I:1.2/02	V121	Red	Green	104215
I:1.2/04	V122	Red	Green	104216

Address in PLC	*Name of the valve*	*Wire to the sink of discrete input module*	*Wire to the 24 VDC of discrete input module*	*Cable no. (from 37-pin to PLC discrete I/O)*
I:1.2/06	V125	Red	Green	104217
I:1.2/08	V126	Red	Green	104218
I:1.2/10	V128	Red	Green	104219
I:1.2/12	V208	Red	Green	104220
I:1.2/14	V302	Red	Green	104221
I:1.3/00	V304	Red	Green	104222
I:1.3/02	V403	Red	Green	104223
I:1.3/04	V502	Red	Green	104224
I:1.3/06	V504	Red	Green	104225
I:1.3/08	V129	Red	Green	104292
I:1.3/10	V119A	Red	Green	104478
I:1.3/12	LN2	Red	Green	104479
I:1.3/14	H2_cave_alrm	Red	Black	104480
I:1.3/15	H2_cave_warn	White	Green	104480
I:1.5/00	HE_RGA_SET	Red	Green	104481
I:1.5/02	H2_vent_alrm	Red	Black	Not assigned
I:1.5/03	H2_vent_warn	White	Green	Not assigned

Table 2: Output addresses at PLC for the solenoid operated valves

Address in PLC	*Name of the Valves*	*Wire to Source of discrete output module*	*Wire to common of discrete output module*	*Cable no. (from 37-pin to PLC discrete I/O)*
O:1.4/00	V100	Red	Black	104192
O:1.4/01	V114	Red	Black	104194
O:1.4/02	V201	Red	Black	104196

Address in PLC	*Name of the Valves*	*Wire to Source of discrete output module*	*Wire to common of discrete output module*	*Cable no. (from 37-pin to PLC discrete I/O)*
O:1.4/03	V204	Red	Black	104198
O:1.4/04	V205	Red	Black	104200
O:1.4/05	V207	Red	Black	104202
O:1.4/06	V303	Red	Black	104204
O:1.4/07	V129	Red	Black	Not assigned

Table 3: Panelview addresses for the request buttons (to open or close the valves, or read a pressure/flow set, or override the interlock) and the status of the requested button.

Name of the valve or command	*Panelview address for the request button*	*Panelview address for the requested button status*
V100_BTN_REQ	I:1.24/00	O:1.24/01
V114_BTN_REQ	I:1.24/01	O:1.24/03
V201_BTN_REQ	I:1.24/02	O:1.24/05
V204_BTN_REQ	I:1.24/03	O:1.24/07
V205_BTN_REQ	I:1.24/04	O:1.24/09
V207_BTN_REQ	I:1.24/05	O:1.24/11
V303_BTN_REQ	I:1.24/06	O:1.24/13
NO_INTLK_V100	I:1.24/07	O:1.26/08
NO_INTLK_V114	I:1.24/08	O:1.26/09
NO_INTLK_V204	I:1.24/09	O:1.26/10
NO_INTLK_V207	I:1.24/10	O:1.26/11
NO_INTLK_V303	I:1.24/11	O:1.26/12
PRESSURE_SET1_REQ	I:1.24/12	O:1.26/13
PRESSURE_SET2_REQ	I:1.24/13	O:1.26/14
PRESSURE_SET3_REQ	I:1.24/14	O:1.26/15
V129_BTN_REQ	I:1.24/15	O:1.27/00

Name of the valve or command	***Panelview address for the request button***	***Panelview address for the requested button status***
FLOW_BTN_REQ	I:1.25/00	O:1.27/02
Testmode_BTN_REQ	I:1.25/01	O:1.27/03

Table 4: Panelview addresses for the actual status of the valves.

Name of the valve	***Panelview address for actual status***	***Name of the valves***	***Panelview address for actual status***
V100	O:1.24/00	V128	O:1.25/11
V114	O:1.24/02	V115	O:1.25/12
V201	O:1.24/04	V208	O:1.25/13
V204	O:1.24/06	V302	O:1.25/14
V205	O:1.24/08	V304	O:1.25/15
V207	O:1.24/10	V403	O:1.26/00
V303	O:1.24/12	V502	O:1.26/01
V107	O:1.24/14	V504	O:1.26/02
V108	O:1.24/15	V129	O:1.26/03
V109	O:1.25/00	V119A	O:1.26/04
V110	O:1.25/01	LN2	O:1.26/05
V111	O:1.25/02	H2_cave_alrm	O:1.26/06
V113	O:1.25/03	H2_cave_warn	O:1.26/07
V117	O:1.25/04	H2_vent_alrm	O:1.27/04
V119	O:1.25/05	H2_vent_warn	O:1.27/05
V120	O:1.25/06		
V121	O:1.25/07		
V122	O:1.25/08		
V125	O:1.25/09		
V126	O:1.25/10		

- **design**

Deadlines, Desired Controls and Screen Displays (as per K:\NPDG_schematic18.dwg) for the NPDGamma Target.

1) 30-ft wire runs are desired between the I/O of the PLCs and the components of the gas handling system (GHS). Prior to assembly of the GHS, the wiring can be cut to length, labeled, and terminated with connectors.

2) Desire Panel View display pages to allow control of the 6 normally closed solenoid valves located in the GHS and to display the component layout are:
   i) H2 system (1xx),
   j) Main Vacuum System (2xx),
   k) RGA System (3xx), and
   l) He System (4xx),
   m) Temperature sensor values and graphic display of the sensor locations (9, to be supplied),
   n) Pressure values indicated by the 9 Omega PTs (0.5-5.5V output signals),
   o) Readout of the 2 mass-flow meters (FM401 and FM101),
   p) Valve-control interlocks (activated by PT setpoints), and override controls.

3) Closed/Not-Closed indication of 22-25 manual round-knob valves via one microswitch and 2 LEDs attached to each valve. If the LEDs are powered with a 9V supply placed near the valves, the voltage polarity reversal across the microswitch when it changes state may be used by the PLC. This arrangement allows 2-conductor hookup for each valve.

4) Interface the PLC with the temperature output signals of 7 silicon diodes (standard curve 10) activated and monitored by the Lakeshore 215 8-channel sensor monitor.

5) Interface the PLC with the Lakeshore DRC-91C Temperature Controller to:
   a) Obtain the temperatures indicated by 2 silicon-diode sensors
   b) Adjust the control setpoint of the unit. The existing slow and fast jog buttons Jim programmed into the View Panel will be great for this.

7) During power outages of less than 20 minutes, the control system must continue to monitor and display (View Panel) the target pressures and temperatures. Beyond 20 minutes, the PLC must shut down gracefully. There are 4 UPSs in house that might together handle most of the load to keep the 2 Lakeshore units and the 9 Omega pressure-sensor controls.

DEVICE	States required to satisfy interlock(s).	NOTES
V112		
V127		

V201		
V204		
V206		
V207		

V303		
PT202		
PT302		

- **data sheets**

- **test results**

Cave hydrogen safety

- **Electricity (H. Nann, 5-1-01)**

The whole point of the safety design is to allow for the possibility to use ordinary equipment in the experimental cave by preventing hydrogen from entering the cave in the first place. We argue that therefore we do not need explosion-proof electronics. This argument was agreed to in the second safety meeting by the safety committee. The robust design of the flask and vacuum jacket plus the addition of the helium jacket makes release of hydrogen into the cave extremely unlikely.

- **Ventilation**

  - **design and specifications (H. Nann, 6-10-01)**

We intend to design the ventilation as needed for personnel comfort and the needs of the experiment. This air flow is not a primary part of the hydrogen safety system since the hydrogen is considered to be adequately contained by the robust hydrogen flask, vacuum vessel, and helium jacket.

The exhaust port will be located near ceiling of cave in a location, which allows for the best neutron shielding. Ventilation rate: 6,000 l/min (200 cfm) (this means that we change air in the cave every 10 min.)

Fan motor either explosion-proof or mounted outside air stream. Rotor to be non-sparking construction. Exhaust ducted to outside of building.

  - **data sheets**
  - **testing**

- **H_2 sensors**
  - **specifications**

The cave will be equipped with two H_2 monitors and two low-oxygen monitors. The low-oxygen monitor will be connected to the local alarm. The H_2 sensors will be interlocked to the power of the cave.

  - **design**
  - **data sheet**

- **test results**

Radiological safety (H. Nann, 5-20-01)

The exposure of various items of the experiment to the neutron beam for a time of approximately one year will cause activation of certain components. Almost all of this activation will be prompt gammas from cold neutron capture. However, there are a couple of sources of tritium generation in the experiment. Here we make estimates of the amount of tritium generated in the hydrogen target due to (A) interactions with ^{3}He impurities in the ^{4}He jacket, (B) interactions with deuterium in the LH_2 target.

(A) ^{3}He(n,p)^{3}H

(n,p) cross section at $E_n = 1$ keV: $\sigma(1\text{ keV}) = 27$ b

Assume $\sigma \propto 1/v$ dependence $\Rightarrow$ $\sigma(4\text{ meV}) = 1.35 \times 10^4$ b $= 1.35 \times 10^{-20}$ cm^2

Natural abundance of ^{3}He: 1.37×10^{-6}

At STP: 22.4 L of helium contain 6.02×10^{23} atoms

1 cm^3 at 1.2 atm contains 3.22×10^{19} atoms

1 cm^3 of natural He at 1.2 atm contain 4.41×10^{13} atoms of ^{3}He.

Assume a target thickness of 1 cm $\Rightarrow$ d(3He) = 4.41×10^{13} atoms/cm^2

Neutron flux: $\Phi = 1 \times 10^{10}$ neutrons/sec

Luminosity: $L = \Phi \cdot d = 4.41 \times 10^{23}$ s^{-1} cm^{-2}

Tritium yield: $Y = L \cdot \sigma = 5954$ s^{-1} $= 1.88 \times 10^{11}$ per year

Activity: $A = \lambda \cdot N$

Half-life of tritium: $t_{1/2} = 12.33$ yr $= 3.89 \times 10^8$ s

$$\lambda = \frac{\ln 2}{t_{1/2}} = 1.78 \times 10^{-9}\ \text{s}^{-1}$$

$$A = (1.78 \times 10^{-9}\ \text{s}^{-1})(1.88 \times 10^{11}) = 335\ \text{s}^{-1}$$

(B) $^{2}H(n,\gamma)^{3}H$

(n,γ) cross section at 25 meV: $\sigma(25\ \text{meV}) = 5.2$ mb

Assume $\sigma \propto 1/v$ dependence $\Rightarrow$ $\sigma(4\ \text{meV}) = 13\ \text{mb} = 1.3 \times 10^{-26}\ \text{cm}^2$

Natural abundance of ^{2}H: 1.48×10^{-4}

20 L of LH_2 density of LH_2: $\rho = 66\ \text{kg/m}^3$
mass of LH_2: $m = \rho V = (66\ \text{kg/m}^3)(20 \times 10^{-3}\ \text{m}^3) = 1.320\ \text{kg} = 1320\ \text{g}$

molecular mass of H_2: $M = 2.016$ g/mol

number of moles: $n = m/M = (1320\ \text{g})/(2.016\ \text{g/mol}) = 655$ mol

number of atoms: $N = n\, N_A = (655\ \text{mol})(6.02 \times 10^{23}\ \text{mol}^{-1}) = 3.94 \times 10^{26}$

20 L of LH_2 contain 5.83×10^{22} deuterium nuclei. They are distributed over a circular area of 30 cm diameter.

$$d(^{2}H) = 8.25 \times 10^{19}\ \text{nuclei/cm}^2$$

Neutron flux: $\Phi = 1 \times 10^{10}$ neutrons/sec

Luminosity: $L = \Phi \cdot d = 8.25 \times 10^{29}\ \text{s}^{-1}\ \text{cm}^{-2}$

Tritium yield: $Y = L \cdot \sigma = 1.07 \times 10^{4}\ \text{s}^{-1} = 2.78 \times 10^{10}$ per month

Activity: $A = \lambda \cdot N$

$$A = (1.78 \times 10^{-9}\ \text{s}^{-1})(2.78 \times 10^{10}) = 50\ \text{s}^{-1}$$

Warnings, Alarms, and Interlocks (J. Novak, H. Nann, 6-22-01)

We propose a three-tiered hierarchy of status indicators for the system as follows:

Normal: The system operating as designed with all interlocks and sensors active and within set ranges.
Warning: Some sensor(s) are at values between low and high trip points. Local indication (horn, lights, signs) and possibly phone dialer initiated. Operator attention is required but automatic shutdown action is not needed. Necessary personnel may be near the equipment with caution; others should stay away.
Alarm: Some sensor(s) have exceeded their high trip levels. Automatic safety and/or shutdown systems take over. Local indications (horns, lights, signs). All personnel should leave the area. Neutron beam in experiment flight path shut off. CCR automatically notified. Phone dialer initiated.

Sensor	**Location**	**Trip point**	**Action**
H_2 concentration #1 H_2 concentration #2	Cave, in stagnant air near ceiling	10% of LEL	Warning
H_2 concentration #1 H_2 concentration #2	Cave, in stagnant air near ceiling	25% of LEL	Alarm. H_2 System shutdown and rapid H_2 dump. Electrical power in cave shut off.
Air flow	Cave exhaust	70% of normal flow	Warning
Vacuum (pressure) sensor	Vacuum vessel	Bad	Warning
H_2 concentration	Vacuum vessel	Low	Warning
H_2 concentration	Vacuum vessel	High	Alarm. H_2 System shutdown

Sensor	Location	Trip point	Action
			and rapid H_2 dump.
RGA	Vacuum vessel	He peak > Low	Warning
RGA	Vacuum vessel	He peak > High	Alarm. H_2 System shutdown and rapid H_2 dump.
RGA	Vacuum vessel	N_2 peak > Low	Warning
RGA	Vacuum vessel	H_2O peak > Low	Warning
He pressure	Helium jacket	p < 3 psig	Warning
H_2 pressure	Target gas in condenser unit	p > 11 psig, p < 9 psig	Warning
O_2 concentration #1 O_2 concentration #2	Cave, at normal breathing space elevation	Low	Warning

- **signals connected to facility**
- **local status signals**